DRAFT

Interim Progress Report

Geochemistry Monitoring Program

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I. Introduction

The geochemical monitoring program has undertaken two related responsibilities:

1) Conduct a detailed analysis of the chemistry and dynamics of the shallow groundwater system on the Lower East Rift (LERZ); and

2) Evaluate the chemical composition of the geothermal fluids from the geothermal reservoir currently under development on the Kilauea East Rift Zone (KERZ). The objectives of the first effort are to characterize the baseline compositions of the shallow groundwater in the LERZ, to assess whether the geothermal development is having an adverse affect on the groundwater resources, develop a conceptual model for groundwater flow and mixing on the LERZ and to provide a data base with which to develop and validate a numerical model of this groundwater system. Analysis of the geothermal fluid compositions will provide us with the data necessary to determine whether shallow groundwater contamination is occurring and will enable us to assess some of the impacts that fluid production may be having on the long term viability of the geothermal reservoir.

The shallow groundwater monitoring program has employed both continuous downhole monitoring instruments as well as repeated sampling of a variety of shallow groundwater sources located within and near the KERZ. Groundwater sources were chosen for monitoring included wells that were in close proximity to, or down-gradient from, the geothermal system as well as sources that could provide baseline data that were unlikely to be affected by geothermal activities. Analysis of reservoir fluids have included both the liquid and steam phases generated by the geothermal production wells supplying steam to the PGV facility.

The results that have been obtained to date for the groundwater monitoring program have shown that the groundwater system in lower Puna is very complex and is much different from those found elsewhere in Hawaii. Comparison of the variations in groundwater chemistry with the compositions of the geothermal fluids has not shown any detectable impact on groundwater quality from the geothermal development activities up to the present time. Analyses of the geothermal fluids has also shown that the fluids produced by the commercial production wells in the reservoir currently under development are quite different from those produced by the earlier HGP-A well, but have also found that substantial changes in production chemistry have occurred since production began in early 1993.

II. Groundwater Hydrology Program

Prior Work

During the last two decades a number of studies have been conducted on the hydrology and geochemistry of the KERZ. Although the LERZ has not had a dense network of wells, there has been enough access to the basal groundwater to provide a tentative conceptual model of the hydrologic system there. The general characteristics of the groundwater system can be summarized as follows:

1) The groundwater flow gradient within the basal lens is generally toward the east and is driven by rainfall recharge on the upper slopes of Mauna Loa and Kilauea volcano that is estimated to be as high as several billion gallons per day. The rift zone acts as a retarding structure to flow and tends to direct groundwaters to the northeast above the rift whereas rainfall recharge on the south flank of Kilauea, as well as water that passes through or over the rift, tends to flow in a south-easterly direction toward the coast. Both the recharge data and radioactive tritium analyses have shown that the rate of through-put of groundwater beneath the region is quite high: the age of the groundwater is less than a dozen years and the discharge rates at coastal springs are estimated to be on the order of hundreds of millions of gallons per day.

2) The chemical compositions of the basal waters show a high degree of variability over the region. Far north of the rift, groundwater tends to have very low dissolved solids contents but, as the rift zone is approached, the concentration of the alkali and alkaline earth metals (sodium, potassium, magnesium, and calcium) increase as do the concentrations of anions (chloride, sulfate, and carbonate). Within and south of the rift, many wellwaters show substantial concentrations of seawater-derived fluids that have been altered by moderate to high temperature interactions with the rocks of the KERZ. The groundwaters also tend to be highly stratified: thermal saline water is found to overlie cooler, less saline fluids.

3) Temperature variations follow a similar pattern to that of the chemical compositions: far north of the rift groundwater temperatures are relatively low but, as the rift is approached, temperatures rise. Within and south of the rift, nearly all wells show elevated temperatures with some having temperatures as high as 95°C.

Nearly all of the published investigations have evaluated the areal variation in groundwater chemistry. Although temporal changes in the basal water chemistry are apparent from the substantial variations in compositions found between samples taken from the same well , a systematic study of these variations has not been published prior to our undertaking the present investigation.

Field Design of Monitoring Program

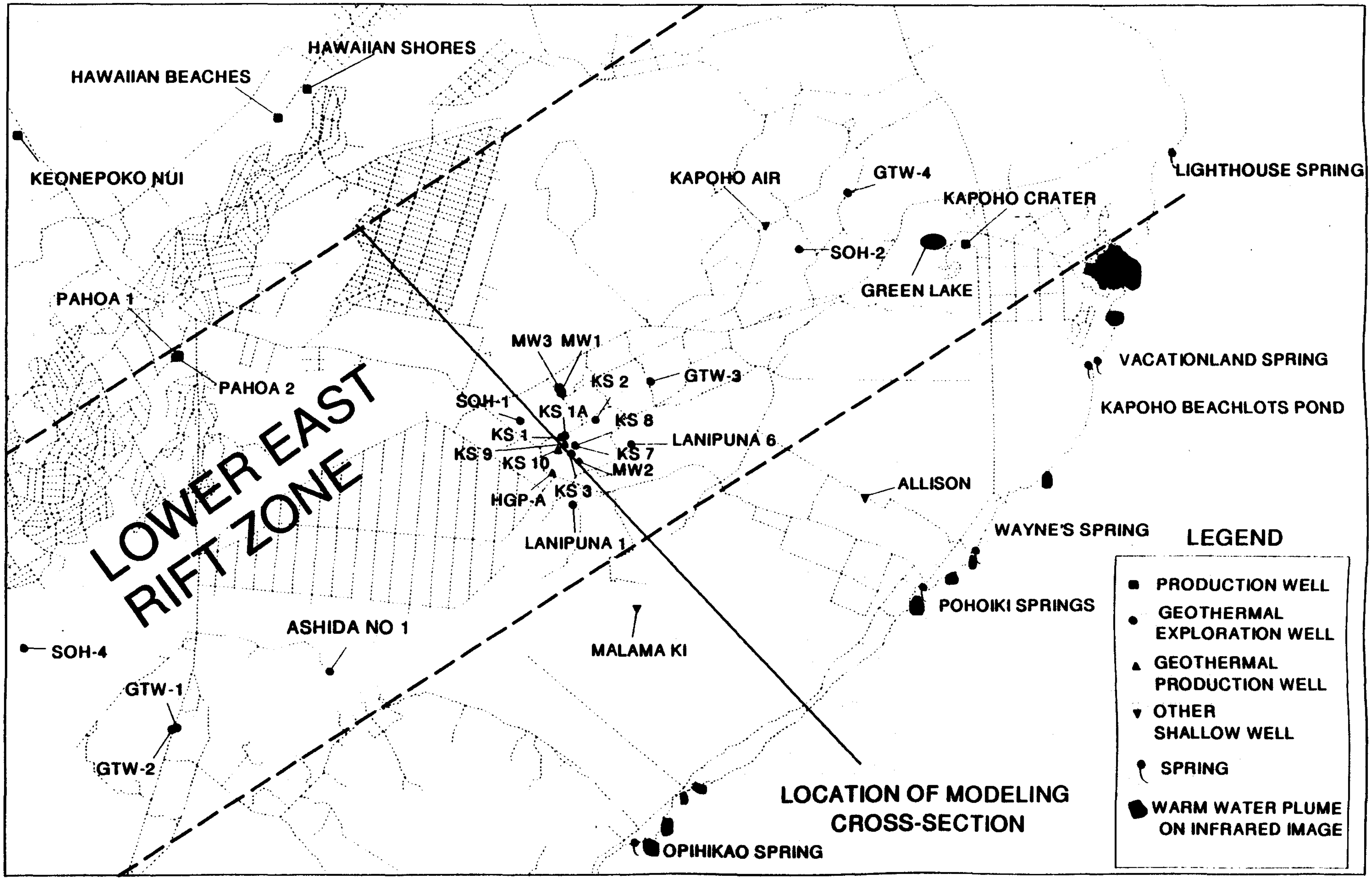
Thirteen shallow wells are known to have been drilled in the lower Puna region during the last four decades (Table 1, Figure 1). Three of these wells either did not penetrate to the water table (GTW 1 and 2) or have been plugged by debris (GTW-4). The remaining ten wells have all been sampled in the recent past and all are recognized as penetrating into the basal water table. In order to provide data for modelling the lower Puna groundwater system, continuous monitoring of water levels, salinity and temperature were conducted in a subset of key wells within and near the rift. The wells within the rift that for which monitoring was attempted included the Malama Ki well, the Kapoho Airstrip well, Geothermal Test Well 3 (GTW-3), Monitoring Well 2 (MW-2), and the Allison Well. Most of the other wells in the region have permanently installed pumps in them and, hence, we were unable to gain access to the water table. An addition well north of the rift zone, in Paradise Park, was monitored for the same characteristics as those within the rift in order to provide a "non-geothermal" or non-rift zone baseline data for comparison to those wells in our primary monitoring set.

In addition to the continuous monitoring data, less frequent but more detailed analysis and documentation of the fluid chemistry at these wells was also performed. First priority was given to those wells that were believed to be at risk of contamination from potential geothermal discharges or those that would provide an "early warning" that geothermal fluids from the commercial development were being discharged into the shallow groundwater. This set of wells included MW-1, 2, and 3, GTW-3, Allison Well, the Kapoho Airstrip well, and the Kapoho Shaft. In addition to these, the Pahoa wells and the Malama Ki well are included in the monitoring program to enable us to evaluate natural temporal changes in groundwater that are unlikely to be associated with development of the geothermal resource. Both wells are located west of the production and reinjection field and, hence, are either up-gradient or cross-gradient of the well field.

TABLE I

Lower Puna Wells

Name	Abbrev.	I.D. Number	Lat	Long.	Elevation	Depth Drilled	Date Drilled	Use
Paradise Park	PPW	3588-01	19.6	155	145	168	1981	Obs.
Pahoa - 1	Pah - 1	2986-01	19.5	154.9	705	755	1960	Municipal
Keauohana - 1	KHW-1	2487	19.4	155	752	802	1961	Municipal
Kapoho Airstrip	KAW	3081-01	19.5	154.9	287	3373	1961	Irr.
Kapoho Shaft	KSW	3080-01	19.5	154.8	38	46	1965	Municipal
PGV Monitoring 1	MW-1	2983-01	19.5	154.9	610	725	1990	Utility
PGV Monitoring 3	MW-3	2983-02	19.5	154.9	610	720	1991	Utility
Geothermal Test 3	GTW-3	2982-01	19.5	154.9	563	690	1961	Obs.
PGV Monitoring 2	MW-2	2883-07	19.5	154.9	588	640	1991	Obs.
Allison Well	AW	2881-01	19.5	154.9	132	140	1973	Irr.
Malama Ki	MKW	2783-07	19.5	154.9	274	319	1962	Obs.


HAWAIIAN SHORES
HAWAIIAN BEACHES
KEONEPOKO NUI
KAPOHO AIR
GTW-4
LIGHTHOUSE SPRING
KAPOHO CRATER
SOH-2
GREEN LAKE
PAHOA 1
PAHOA 2
MW3
MW1
KS 2
GTW-3
VACATIONLAND SPRING
KAPOHO BEACHLOTS POND
SOH-1
KS 1A
KS 8
KS 1
LANIPUNA 6
KS 9
KS 10
KS 7
MW2
HGP-A
KS 3
ALLISON
LANIPUNA 1
WAYNE'S SPRING
LOWER EAST RIFT ZONE
POHOIKI SPRINGS
ASHIDA NO 1
MALAMA KI
SOH-4
GTW-1
GTW-2
LOCATION OF MODELING CROSS-SECTION
OPIHIKAO SPRING
LEGEND
PRODUCTION WELL
GEOTHERMAL EXPLORATION WELL
GEOTHERMAL PRODUCTION WELL
OTHER SHALLOW WELL
SPRING
WARM WATER PLUME ON INFRARED IMAGE

The planned sampling protocol for the program was to collect samples on a bi-monthly to quarterly basis from all groundwater wells. Samples were analyzed for major cations and anions, as well as a selected suite of trace elements. As discussed above, the primary objective of the sampling program is to document current conditions within the basal lens, document naturally occurring changes in water quality, and identify any changes that may occur as a result of commercial development of the geothermal resource in lower Puna.

Equipment Design and Selection Criteria

The present investigation has attempted to design a monitoring program that would provide a data set that would meet the program objectives and overcome some of the difficulties encountered in earlier studies. Because previous surveys of the groundwater system in Puna have frequently found highly variable groundwater compositions as a result of intermittent sampling, continuous monitoring of water levels, temperatures, and conductivity were considered to be essential to the development of an accurate model of the dynamics of the groundwater system on the LERZ. The data recovered was expected to allow us to track changes in the conditions and compositions of the basal groundwaters and enable us to relate them to changes in rainfall, tidal effects, or other periodic forcing functions that may affect groundwater quality and transport. The desirable design characteristics for the monitoring instruments were as follows:

1) Continuous digital recording of temperature, water level, and conductivity at intervals of one hour or less;

2) Self contained power supply for stations remote from utility power;

3) Stable over long periods of time;

4) Corrosion resistant surfaces to prevent contamination of the well water;

5) Have an operational temperature up to the boiling point of water.

A number of equipment manufacturers were canvassed for equipment that would meet these requirements but only one supplier, Terra Systems, was willing to certify its equipment at the temperatures required for our use. Five instrument arrays were purchased from this supplier for installation in selected monitoring wells around the commercial wellfield.

Because permanent installation of the monitoring arrays would preclude the use of a bailer sampler in these wells, it was necessary to install downhole pumps in the monitored wells to allow sampling for more detailed analysis of the fluid chemistry at periodic intervals. The design criteria for the pumps were:

1) Minimal contamination of the sample from interaction with the pump body or driving (lifting) mechanism;

2) Capacity to lift water against a 650' head (~300 psi pressure);

3) Be operable under field conditions, without electrical power.

The pumps which best met these criteria were manufactured by QED Groundwater Specialists which could supply a pneumatically driven positive displacement pump. The pumping mechanism was a Teflon bladder encased in a stainless steel pressure housing. The bladder was allowed to fill with wellwater and then externally pressurized with compressed air; the only material with which the well water comes in contact is Teflon and stainless steel. Although these pumps are capable of supplying only small volumes of water, repeated cycling with high-pressure air (500 psi) was capable of lifting water from a depth of 650' to the surface.

For those groundwater wells for which continuous monitoring data were not collected, a Teflon bailer was employed. Sampling of these wells was done in conjunction with that done by Puna Geothermal Venture in order to provide a cross-check for their analytical contractor and to provide consistent data sets.

Results

A substantial set of data has been collected over the course of this effort. In order to present it in a form that will yield a coherent representation of the spatial and temporal variations observed in the basal groundwaters in Puna, several subsets of data will be presented and discussed. Continuous monitoring data for each well will be presented firs and will be followed by a brief comparative analysis of the monitoring data among the wells. The detailed geochemical data for each well will then be considered with a comparative analysis of the chemical compositions of the basal groundwaters. This will be followed by a discussion of the geochemical data for the deep geothermal wells and an analysis of all the geochemical data with as it relates to the identification of interaction between the development activities in the geothermal field and the shallow groundwater chemistry.

Continuous Monitoring Data

In general terms, the continuous monitoring effort has generated a substantial amount of new and valuable data regarding the dynamic processes that are occurring in the basal groundwater systems that are present on Kilauea's Lower East Rift Zone. This effort did, however, encounter a number of difficulties with most of the equipment used in this effort. Primary among these was that, despite the substantial effort expended screening and evaluating equipment, the monitoring instruments and pumps were frequently unable to withstand the groundwater conditions in lower Puna and, as a result, there were several interruptions of monitoring data over the course of the program. In spite of the difficulties encountered, all the wells but one, GTW-3, have provided continuous data that will enable us to better understand, and model, its interactions with the geothermal system, ocean tidal effects, and rainfall recharge.

Paradise Park Well

The first well that will be described will be our "reference well" located in the Paradise Park subdivision north of the KERZ. This well was monitored to provide a data set that would be free of any effects associated with the rift zone and would serve as a "typical" Hawaii shallow groundwater well. Instruments were installed on 9/21/92 and were withdrawn on 9/17/93. Overall, the equipment worked satisfactorily with only occasional loss of data either due to battery failure or minor glitches in the logging module. Some of the later data in the set may however have been corrupted due to tampering with the well by vandals. Although an effort was made to protect the well and the installed equipment, evidence of repeated efforts to break into the well during August, 1993, made it necessary to remove the equipment in mid-September. A short time after that, one or more individuals were successful in breaking into the wellhead and further vandalized the well by dropping rocks into it. At the present time the well is obstructed by rocks at a depth of about 120 ft. below the surface. The well owner has asked us to restore the well to a useable condition which may require that we bring in a small rig to grind out the obstructing rocks.

In Figures 2 and 3 the weekly averages of the temperature, conductivity, and water level data are presented for 1992 and 1993. Water levels in the well, which are referenced to an arbitrary depth (the location of the monitoring package in the water column), show a range of more than 20 in. over the annual cycle. The step changes in the 1992 water level data reflect relocations of the monitoring package to various depths in the well in order to evaluate the conditions and response characteristics at various levels in the water column. At the shallowest deployment depth, the water level declined to the point that it threatened to expose the instrument package and required that we relocate them to a greater depth in the well. The water level data show that a maximum in water level occurred during the last quarter of 1992, a minimum occurred during May and June of 1993 and was followed by an increase through the third quarter of 1993. The rainfall record for the area (Figure 4) shows elevated rainfall rates during the third and fourth quarters of 1992 followed by a minimum during the first quarter of 1993 and hence indicates that the groundwater levels respond to changes in recharge within periods of less than a few months. We are currently compiling and reducing more detailed rainfall data in order to allow us to better define the response time to changes in rainfall at this and other locations on the rift zone.

Groundwater conductivity shows a long-term trend that is more complex than that of water level. During the period of stable water level (e.g. the second and third quarter, 1993), conductivity gradually increases from about 240 microMhos (uMhos) to more than 250 uMhos until a rainfall event in July begins to replenish the groundwater table. At that time, conductivity drops rapidly but, after the initial drop, it again trends upward in spite of a continuing rise in water level. This pattern is interpreted to reflect an interaction between direct rainfall recharge, that enters the groundwater system vertically and has both a low dissolved solids content and a low conductivity, and transport of water in the basal lens which passes through the local aquifer in a horizontal direction. Because the latter has had a longer contact time with the rock matrix it has a higher dissolved solids content and a higher conductivity. Hence, during periods of low recharge, the primary source of water is horizontal through-flow but, during periods of rapid recharge, vertical influx has a significant impact on both groundwater levels and chemistry. Other short term changes in conductivity during the one-year monitoring interval are also believed to reflect significant rainfall recharge events that replenished the shallow aquifer. We note here again that the very shallow depth of the conductivity instrument in the water column during the second quarter of 1993 may have made it particularly sensitive to these recharge events that were not seen prior to or after this interval.

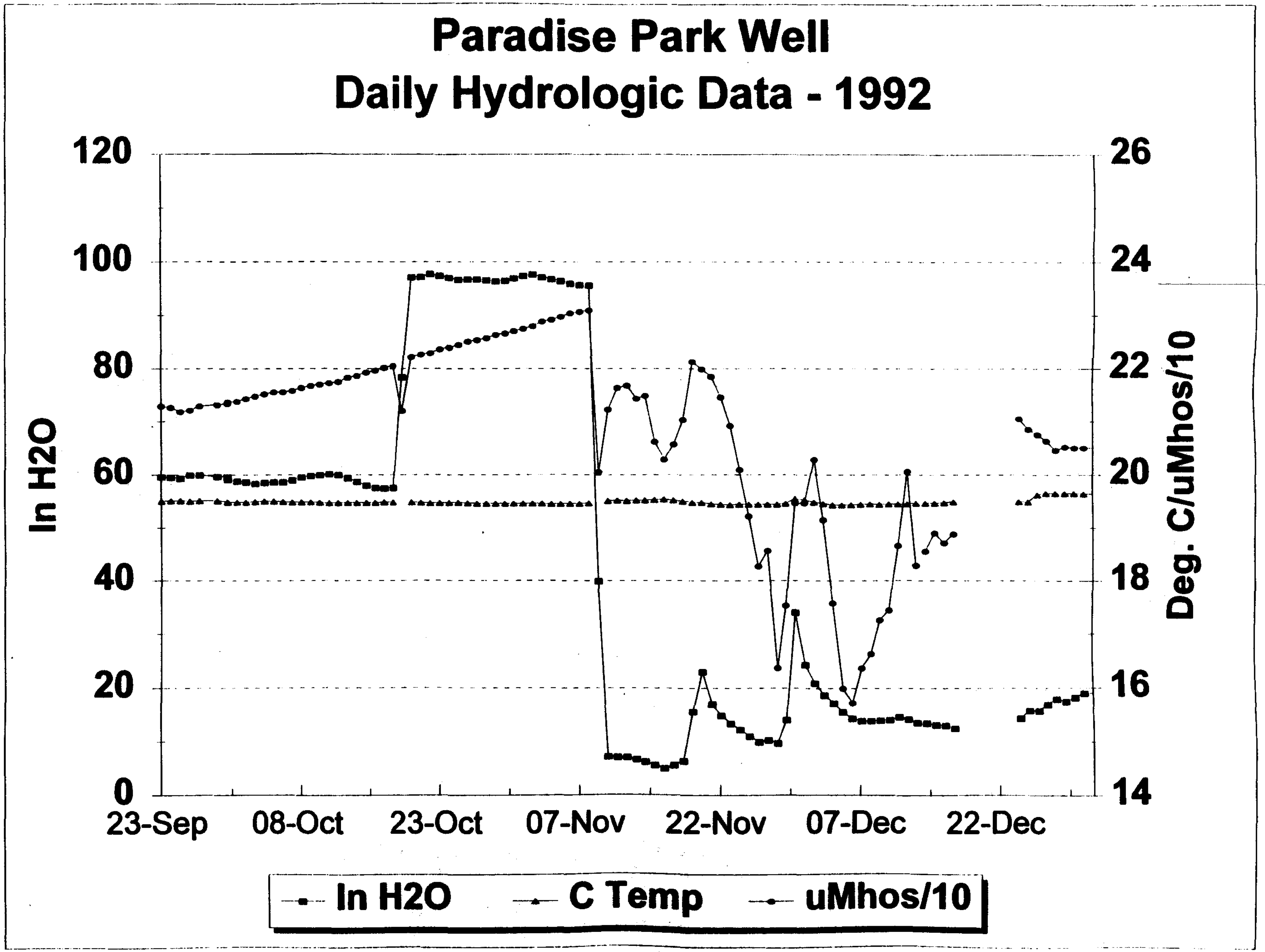
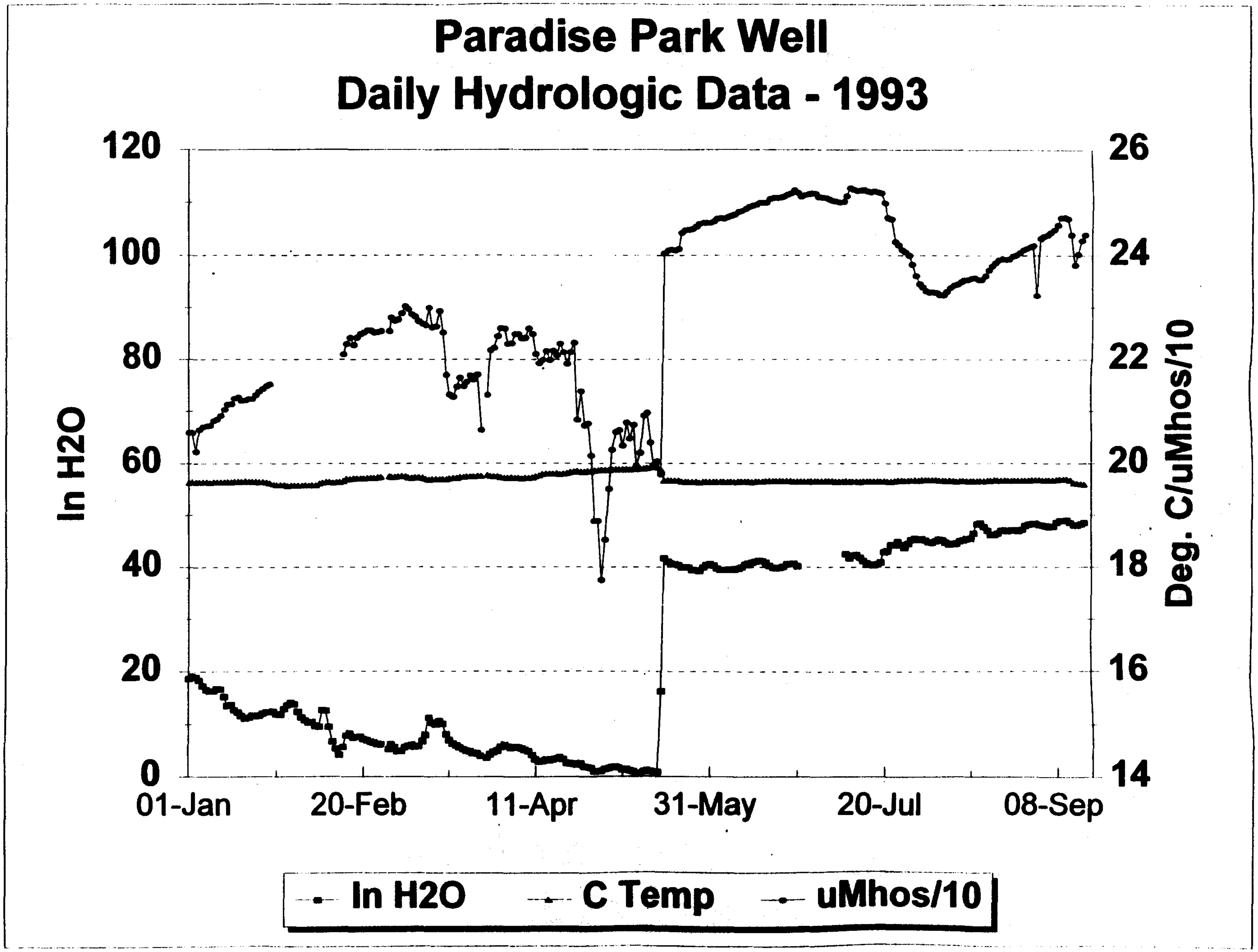

Paradise Park Well
Daily Hydrologic Data - 1992
120
100
80
60
40
20
0
In H2O
26
24
22
20
18
16
14
Deg. C/uMhos/10
23-Sep
08-Oct
23-Oct
07-Nov
22-Nov
07-Dec
22-Dec
In H2O
C Temp
uMhos/10

Figure 2



Paradise Park Well
Daily Hydrologic Data - 1993
120
100
80
60
40
20
0
In H2O
26
24
22
20
18
16
14
Deg. C/uMhos/10
01-Jan
20-Feb
11-Apr
31-May
20-Jul
08-Sep
In H2O
C Temp
uMhos/10

Figure 3

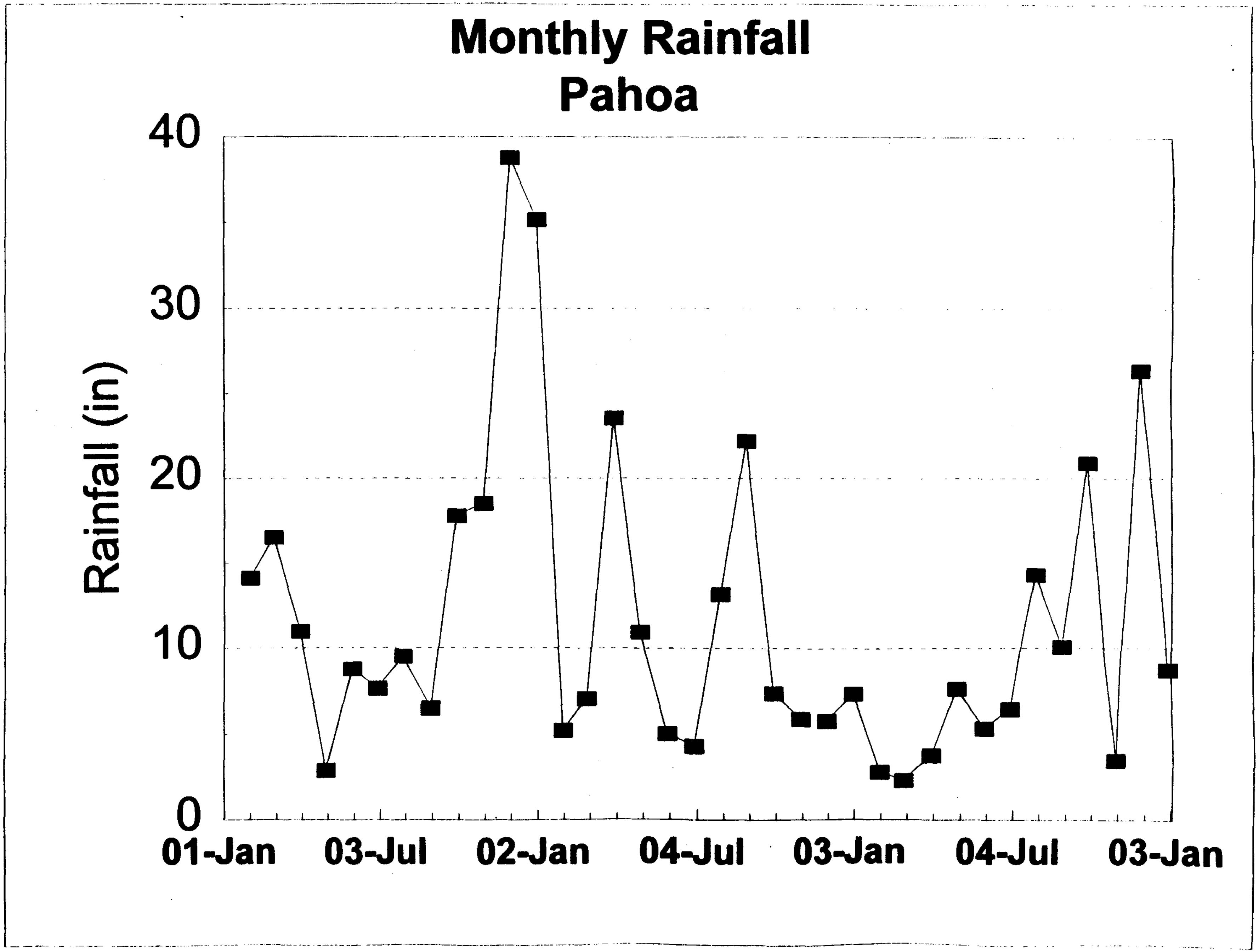

Monthly Rainfall
Pahoa
Rainfall (in)
40
30
20
10
0
01-Jan
03-Jul
02-Jan
04-Jul
03-Jan
04-Jul
03-Jan

Figure 4

In contrast to the substantial changes in water level and conductivity, the groundwater temperature at this site is remarkably constant over the annual cycle. The total range of the water temperature is less than 0.5°C, from 19.5°C to 20°C, for the entire period of monitoring. The only significant change in temperature seen are those associated with rainfall events which appear to increase temperatures by less than 0.2°C. In consideration of the mild seasonal air temperature change, this is not unexpected although, as will be discussed in more detail below, it does indicate that there is little, if any, mixing of waters from different sources (e.g. fresh and geothermal) in this aquifer.

Examination of the hourly data reveals further characteristics of the groundwater system and its chemistry. Figures 5 and 6 present subsets of hourly data for water level, conductivity and temperature. Although not of direct interest to the geochemistry program, the water level shows a strong influence by the semi-diurnal tidal signal. The presence of such a strong signal indicates that the tidal efficiency is high here and, therefore, that the aquifer is highly permeable between the well and the ocean. Comparison of the water level and conductivity at this scale also reveals that conductivity is responding to the changing water levels on a tidal time scale and indicates that the water column in the well is stratified. Figure 5 shows that as water levels fall, the conductivity decreases, and as water level rises, conductivity increases thus suggesting that the surface waters have lower dissolved solids content than does the deeper water. Further evidence for stratification is seen in Figure 6 which shows that, as the water levels fell during March and April 1992, the conductivity response to the tidal signal became much stronger suggesting that the deeper water is more uniform in composition whereas that near the surface of the water table consists of local recharge with a more variable dissolved solids concentration.

The continuous monitoring data from the Paradise Park Well demonstrates several characteristics of a "typical" non-geothermal groundwater aquifer on the east flank of Kilauea Volcano:

1) The well shows a high tidal efficiency and is therefore in close hydraulic communication with the ocean;

2) Rainfall recharge into the groundwater system occurs via two modes - direct (vertical) replenishment from the surface and horizontal flow from up-slope;

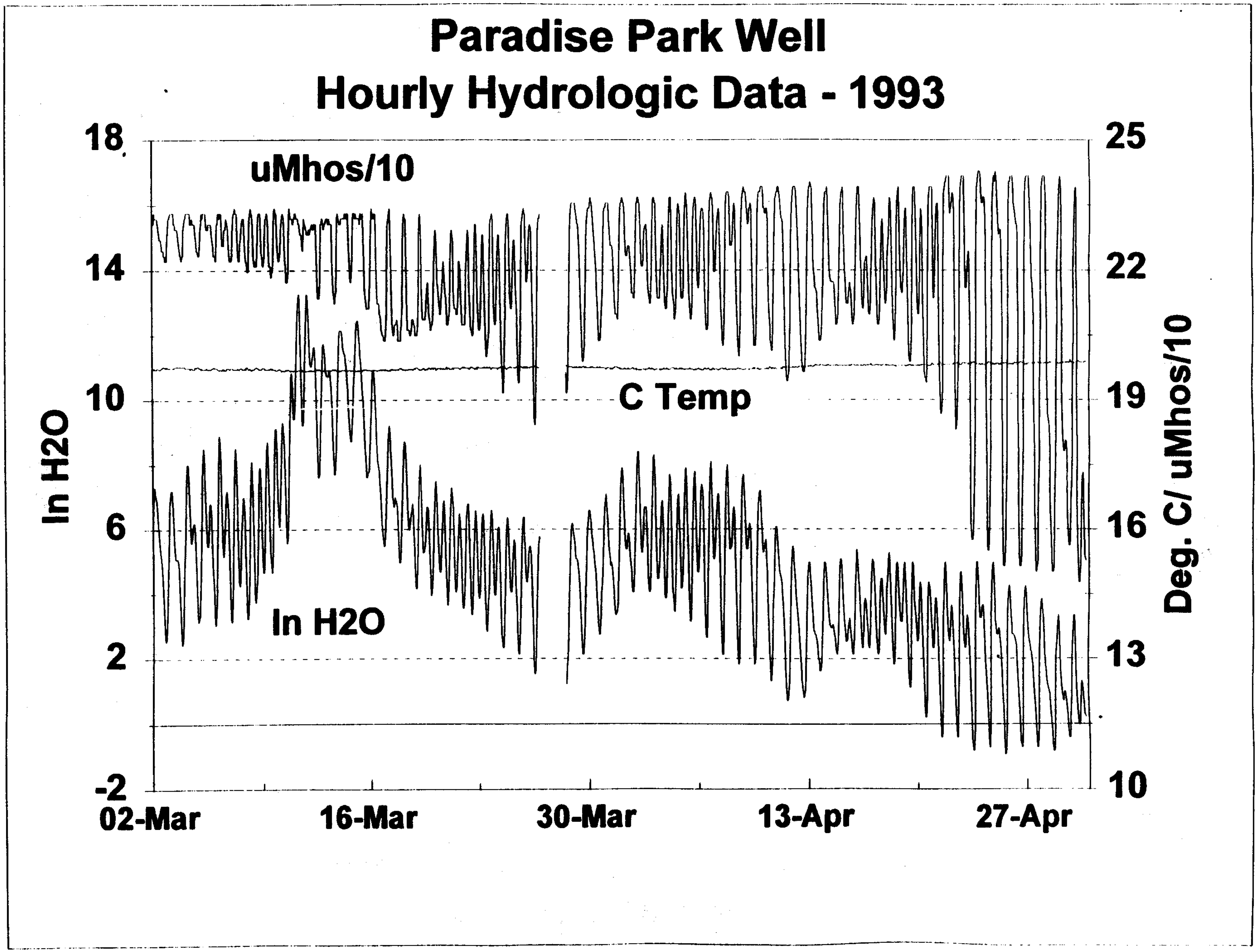

Paradise Park Well
Hourly Hydrologic Data - 1993
uMhos/10
C Temp
In H2O
In H2O
Deg. C/ uMhos/10
18
14
10
6
2
-2
25
22
19
16
13
10
02-Mar
16-Mar
30-Mar
13-Apr
27-Apr

Figure 5

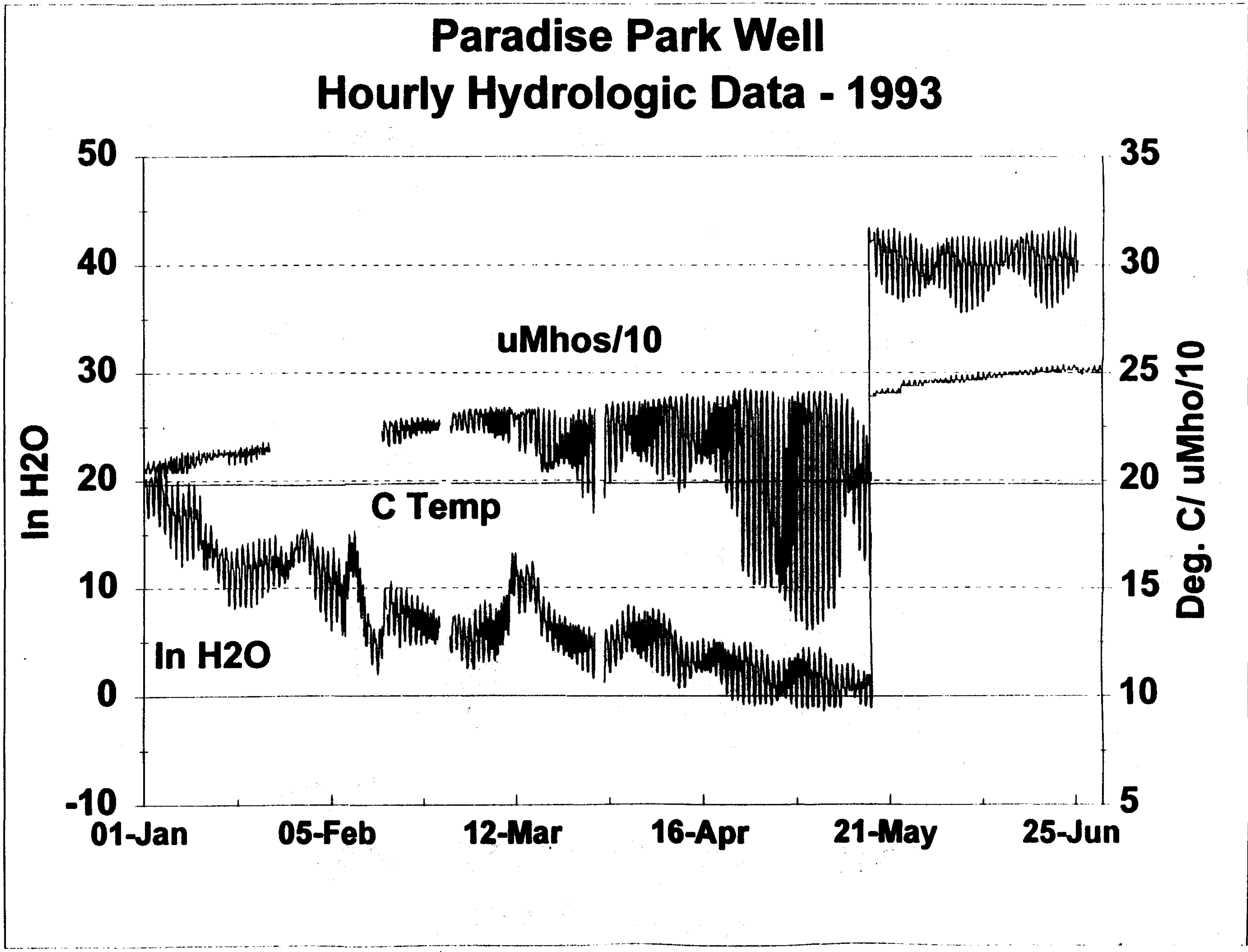

Paradise Park Well
Hourly Hydrologic Data - 1993
50
40
30
20
10
0
-10
35
30
25
20
15
10
5
uMhos/10
C Temp
In H2O
In H2O
Deg. C/ uMho/10
01-Jan
05-Feb
12-Mar
16-Apr
21-May
25-Jun

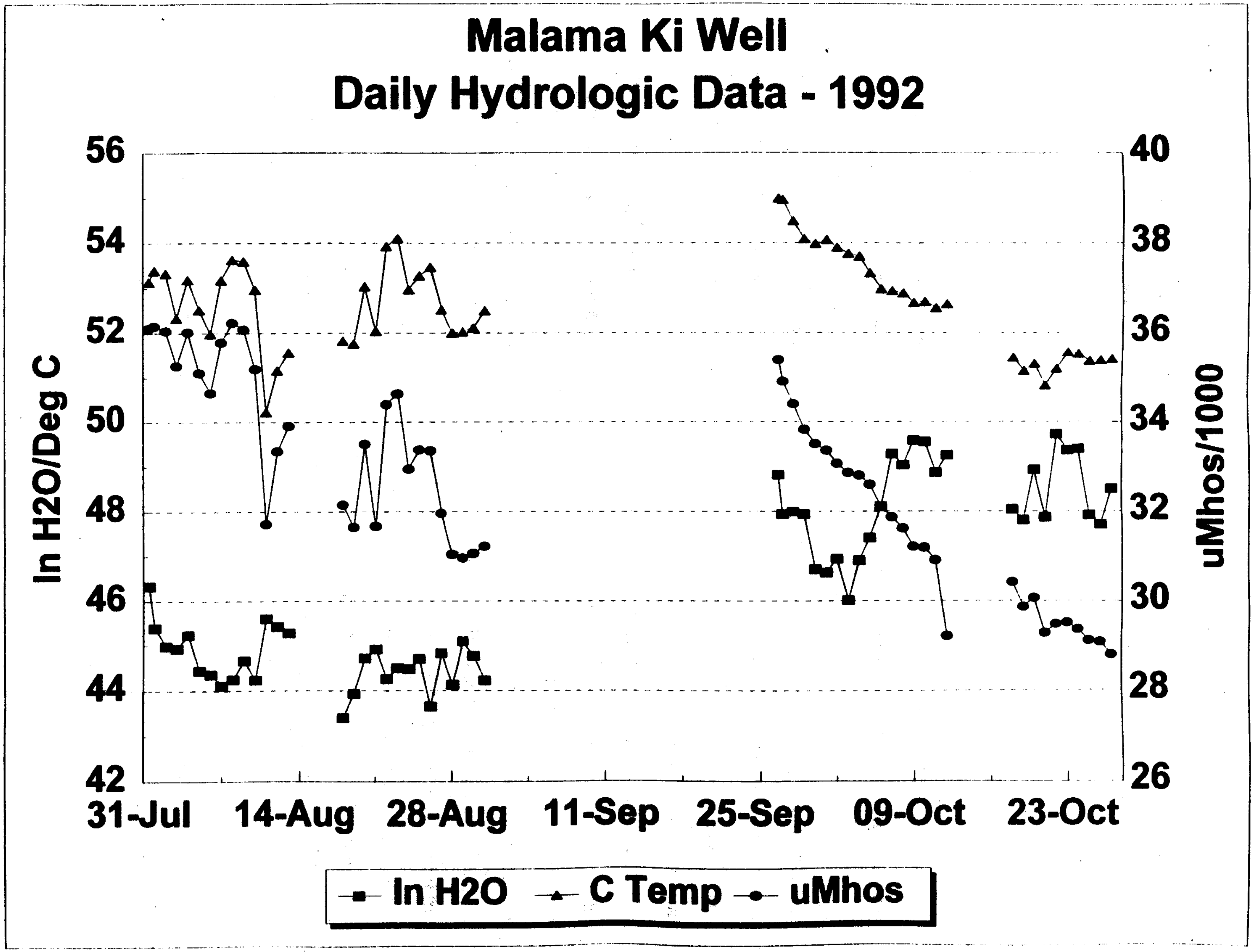
Figure 6

3) Even though the two sources of recharge into the aquifer are both derived from rainfall, there are subtle differences in their conductivities and, therefore, their chemical compositions;
4) The small variations in conductivity that are associated with diurnal tidal fluctuations in water level suggest that the well waters are stratified at a scale of more than a few inches; and
5) The absence of significant temperature changes in the water over the annual cycle studied suggests that seasonal effects on water temperatures are insignificant.

Malama Ki Well

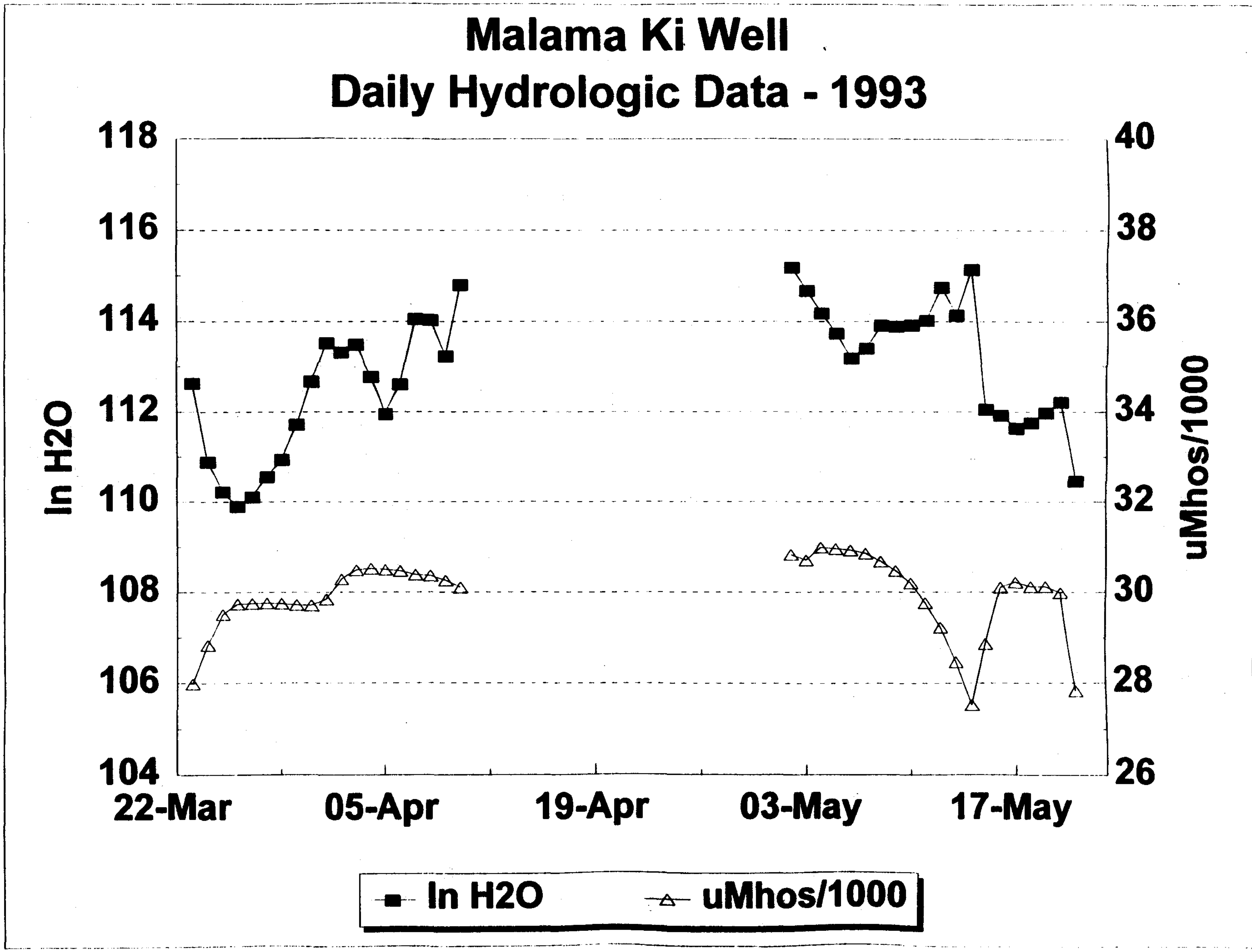
The Malama Ki well is located on the south side of the KERZ and is up-rift and across the hydraulic gradient from the geothermal production field. None-the-less, water temperatures here exceed 55°C indicating that the local groundwater contains significant amounts of natural geothermal discharges. Because it is located outside the expected influence of the geothermal production or reinjection processes, but still contains geothermal discharges, it was chosen as a second reference well that would document the natural response of a mixed basal groundwater to environmental variables.

The daily averages of the hydrologic data at Malama Ki for 1992 and 1993 are shown in Figures 7 and 8. From an operational perspective, the monitoring effort at this site was less successful than that at the Paradise Park Well (PPW). Initial installation of the monitoring equipment occurred in May 1992 but the instruments stopped transmitting data to the data logger by the end of October. The equipment was removed, repaired, and re-installed by March, 1993, but failed again by late May. On recovery of the instruments, they showed deposition of iron oxides on the surface of the instruments; a bladder pump that was installed in the well during the latter interval also showed extensive corrosion on a stainless filter screen. Although the corrosion and deposition characteristics of this groundwater may have contributed to the equipment failure, similar difficulties with the other warm water wells in the rift suggests that elevated groundwater temperatures may have contributed substantially to the malfunction as well. Because the manufacturer had certified the equipment for the temperature conditions found in these wells, the equipment was returned for repair each time it failed. This equipment is currently with the manufacturer undergoing a re-construction.



Malama Ki Well
Daily Hydrologic Data - 1992
In H2O/Deg C
uMhos/1000
56
54
52
50
48
46
44
42
40
38
36
34
32
30
28
26
31-Jul
14-Aug
28-Aug
11-Sep
25-Sep
09-Oct
23-Oct
In H2O
C Temp
uMhos

Figure 7



Malama Ki Well
Daily Hydrologic Data - 1993
118
116
114
112
110
108
106
104
In H2O
40
38
36
34
32
30
28
26
uMhos/1000
22-Mar
05-Apr
19-Apr
03-May
17-May
In H2O
uMhos/1000

Figure 8

In spite of the equipment problems, sufficient data was recovered to provide an assessment of the dynamics of the groundwater here. The daily averages of the groundwater temperature, conductivity, and water level shows that, for the duration of our monitoring work, the daily average water levels ranged over a span of about six inches, the temperatures averaged 54°C and spanned about 5°C, and conductivity averaged 35,000 uMhos and spanned more than 6000 uMhos. Not only are these daily averages much higher than those for the PPW, the range of values for each parameter is also apparently greater (Table 2). The daily data also show that there is a strong correlation between temperature and conductivity but an anti-correlation with water level. When water levels rise, for example in early August 1992, water temperature and conductivity tend to fall. Likewise, in September and October, the water level increases in the well and conductivity and temperature fall.

The hourly hydrologic data (Figures 9 and 10) show that the short-term variations in water levels, temperature, and conductivity are as large or larger than the long-term averages for these parameters. Tidal effects produce an oscillation in water levels of more than ten inches on a daily basis; this is significantly stronger than that in the Paradise Park well which shows a tidal signal of only about five inches even though both wells are nearly equivalent distances to the ocean. The anti-correlation between water level and temperature and conductivity is also evident in this data as well: rising water levels generally correlate with falling temperature and conductivity.

The long-term variations seen in the groundwater conditions are suggested to be predominantly the result of changes in recharge to the south flank of Kilauea: the episodes of increasing water levels in August, September and October, 1992, correlate with increases in rainfall during that period. The hourly data for August (Figure 11) also shows that the rainfall events suppress conductivity and temperature and that these effects recover over periods of a few days. Similarly, the rising water levels in early 1993 correspond to significant rainfall events during that period.

The short term fluctuations in conductivity and temperature that correspond to tidal flux in the Malama Ki Well (MKW) are interpreted to indicate that the basal lens in this area is stratified with warm saline water floating on top of a cooler less-saline water below. Because the degree of stratification in a well is related to the proximity of the discharge point for the warmer fluid, it

TABLE II

Puna Wells Monitored for Hydrologic Paramters

	Type	Water Level Changes LongTerm	Water Level Changes Diurnal	Ave. Temp	Temperature Changes LongTerm	Temperature Changes Diurnal	Ave. Cond.	Conductivity Changes LongTerm	Conductivity Changes Diurnal
ParadisePark	**Reference Non-Geothermal**	20"	7"	19.5°C	+/-0.1	+/-0.05	225	+/-10	+/-5
MalamaKi	**Reference Geothermal**	5"	15"	54°C	+/-2.5	+/-2.5	31,000	+/-4,000	+/-2,500
GTW-3	**Monitor Geothermal**	**ND**	**ND**	93°C	ND	ND	ND	ND	ND
MW-2	**Monitor Geothermal**	**16"**	**0.5"**	**68°C**	**+/-0.5**	**+/-0.75**	**4,550**	**+/-400**	**+/-400**
KapohoAirstrip	**Monitor Geothermal**	**10"**	**12"**	**35.5°C**	**+/-0.75**	**+/-0.9**	**2,700**	**+/-100**	**+/-90**
AllsionWell	**Monitor Geothermal**	**5"**	**30"**	**36.8°C**	**+/-1.5**	**+/-3**	**1,000 (est.)**	**ND**	**ND**

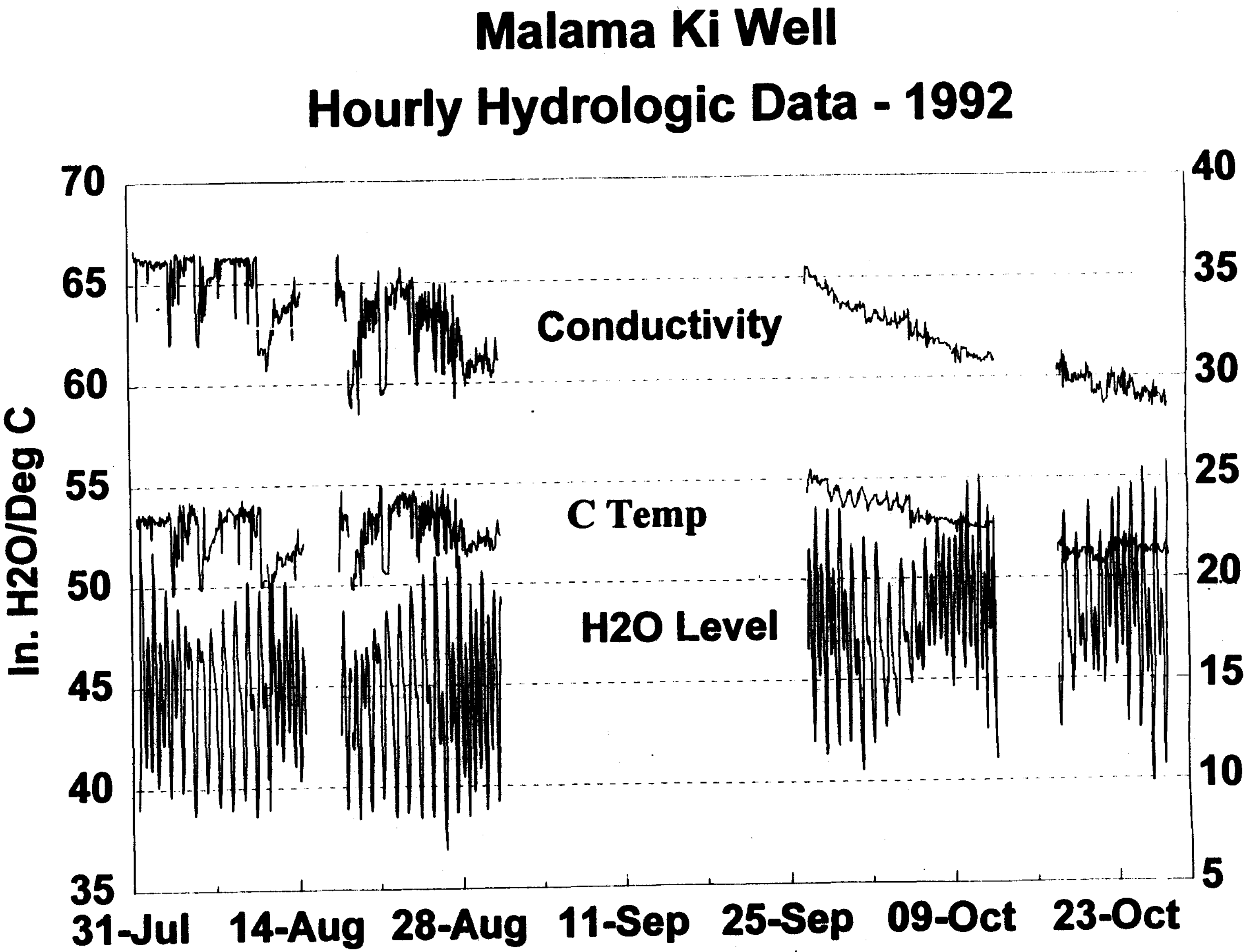

Malama Ki Well
Hourly Hydrologic Data - 1992
70
65
60
55
50
45
40
35
In. H2O/Deg C
40
35
30
25
20
15
10
5
uMho/1000
Conductivity
C Temp
H2O Level
31-Jul
14-Aug
28-Aug
11-Sep
25-Sep
09-Oct
23-Oct

Figure 9

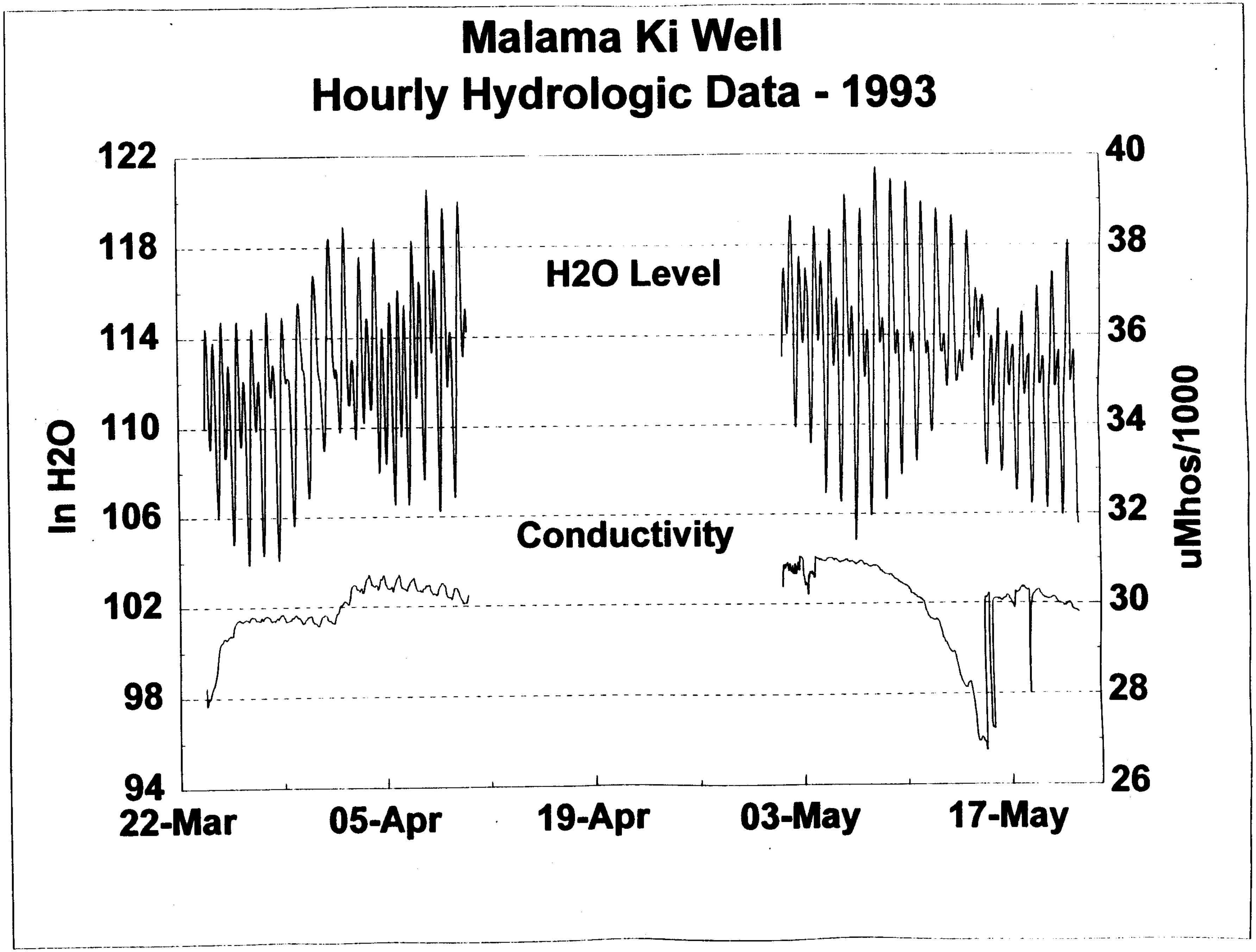

Malama Ki Well
Hourly Hydrologic Data - 1993
H2O Level
Conductivity
In H2O
uMhos/1000
122
118
114
110
106
102
98
94
40
38
36
34
32
30
28
26
22-Mar
05-Apr
19-Apr
03-May
17-May

Figure 10

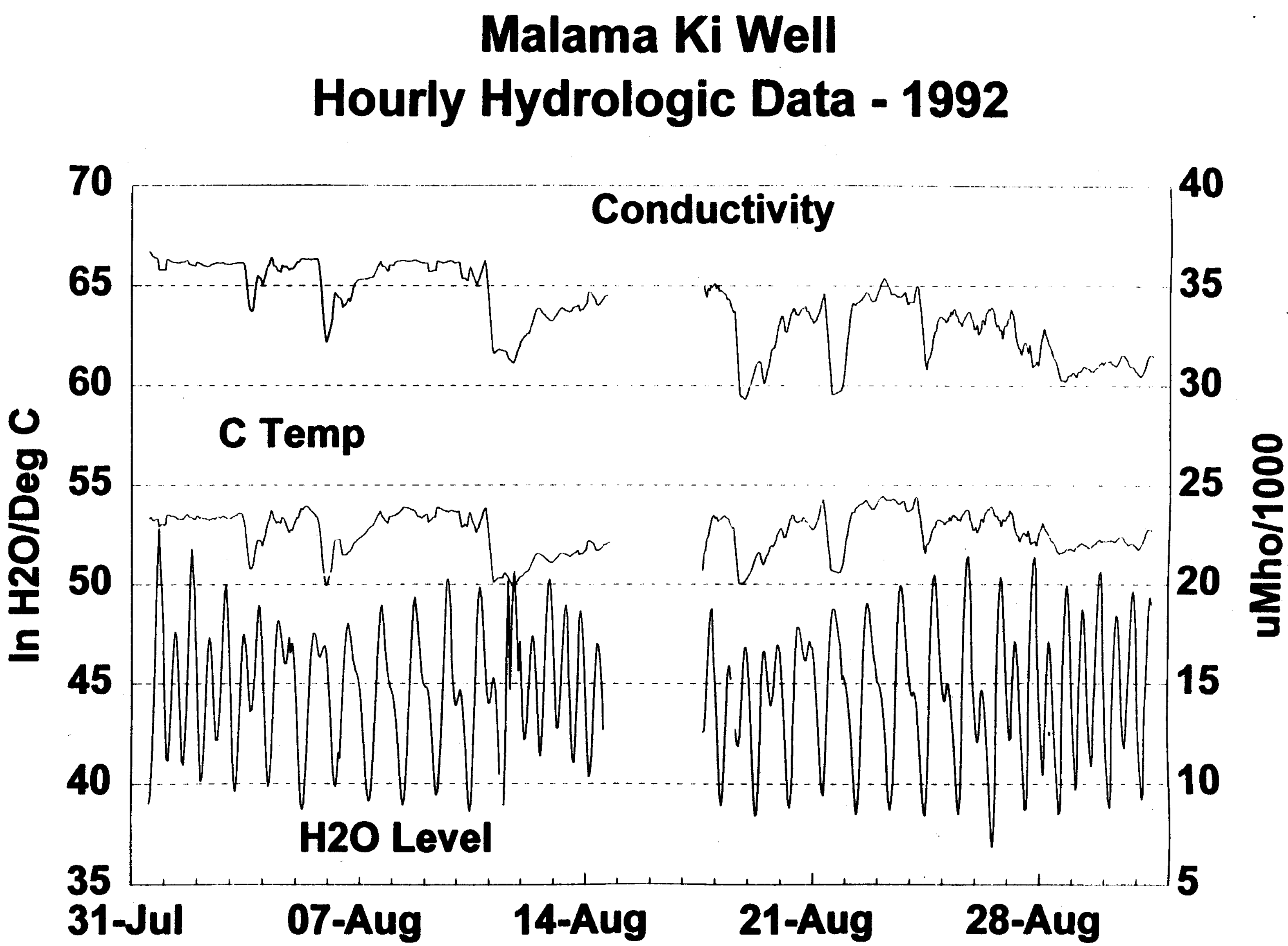

Malama Ki Well
Hourly Hydrologic Data - 1992
Conductivity
C Temp
H2O Level
In H2O/Deg C
uMho/1000
70
65
60
55
50
45
40
35
40
35
30
25
20
15
10
5
31-Jul
07-Aug
14-Aug
21-Aug
28-Aug

Figure 11

is likely that the warm waters in the Malama Ki well are being discharged near the southern edge of the rift. The fact that the warm water is more conductive (i.e. more saline) also indicates that the thermal fluids are more likely to have come from along the southern edge of the rift where seawater has more open access to the rift zone.

In summary, the hydrologic data from Malama Ki demonstrate that

1) There is good communication between this well and the ocean;

2) The basal groundwater lens contains significant amounts of warm water that appear to be discharged from the southern edge of the rift zone upgradient of the well;

3) Strong stratification of the thermal saline waters suggests that the discharge point for the thermal waters is relatively close to the Malama Ki well;

4) Rapid dissipation of the freshwater pulses introduced into the system by rainfall events indicates that water flow through the system must be quite rapid and, hence, that there is a substantial discharge of warm water to have elevated the temperatures of the basal groundwaters by more than 30°C above the normal ambient groundwater temperatures.

Near Field Wells

A subset of four wells in our monitoring program are considered to be the most likely of the wells evaluated to show impacts from the current development activities. Three are located within the surface expression of the KERZ, GTW-3, MW-2, and the Kapoho Airstrip Well (KAW), and are either located in close proximity the production and reinjection activities or are believed to lie down-gradient of them. A fourth well, the Allison Well, is located south of the rift and is and down-gradient from the geothermal field and , hence, might show some response to the development activities. The results for these wells have not found evidence for any impact from development up to the present time but have shown that there are significant variations in the hydrologic parameters not only between different wells but also temporally within a given well.

PGV Monitoring Well -2

MW-2 is the closest of the monitoring wells to the production and reinjection activities in the geothermal field and samples the basal groundwater less than 1 km from the KS-9 and 10 production wells and the KS-3 and 4 reinjection wells. Its close proximity to these activities should allow it to be the first to detect any change in the characteristics of the basal water table that might be a result of production or reinjection.

The effort to obtain hydrologic data from MW-2 met with mixed success due to a number of difficulties arising from the elevated temperature of the groundwaters at this site. The first deployment of monitoring instruments into MW-2 occurred in August 1992; the instruments failed within the first weeks of operation and were recovered at the end of that month and were returned to the manufacturer for reconstruction and repair. The repaired instruments were returned several months later and were re-deployed along with a sampling pump in early April 1993. Although the instrument package operated well after reinstallation, the sampling pump failed in July. Because this well is part of the PGV environmental compliance monitoring system and was sampled on a regular basis, it was necessary to recover the equipment, repair the sample pump, and allow PGV to recover water samples. The depth to the water table in this well is about 175 m (574') and recovery of the equipment became a major difficulty due to the unavailability of a proper power winch. During the planning phases of this program, it was anticipated that the power winch from the USGS logging truck would be available for deployment and recovery of downhole monitoring equipment. The Federal EIS lawsuit denied us access to this equipment and as a result, deployment and recovery of the downhole instrument and pump packages in the deep wells on the rift were much more difficult and dangerous than necessary. In the present instance, we attempted to recover the package using a wire-line winch which jammed the instruments in the hole. In order to recover the equipment and regain access to the water table, it was necessary to contract for a small workover rig to enter the hole with a drill string and fishing tool to recover the equipment. The retrieval operation resulted in extensive damage to the instrument cables which has necessitated their return to the supplier for repair. It is not considered to be feasible to continue monitoring at this site without access to a large power winch.

Although the duration of monitoring in this well is clearly less than was desired, the four months of hourly data recovered provide insights into the groundwater conditions at MW-2 as well as some information the MW-2 well itself. The daily average water level, temperature, and conductivity data for MW-2 are presented in Figure 12. The average water level in the well is seen to vary by about ten inches between April and June 1993 with a progressive decline during

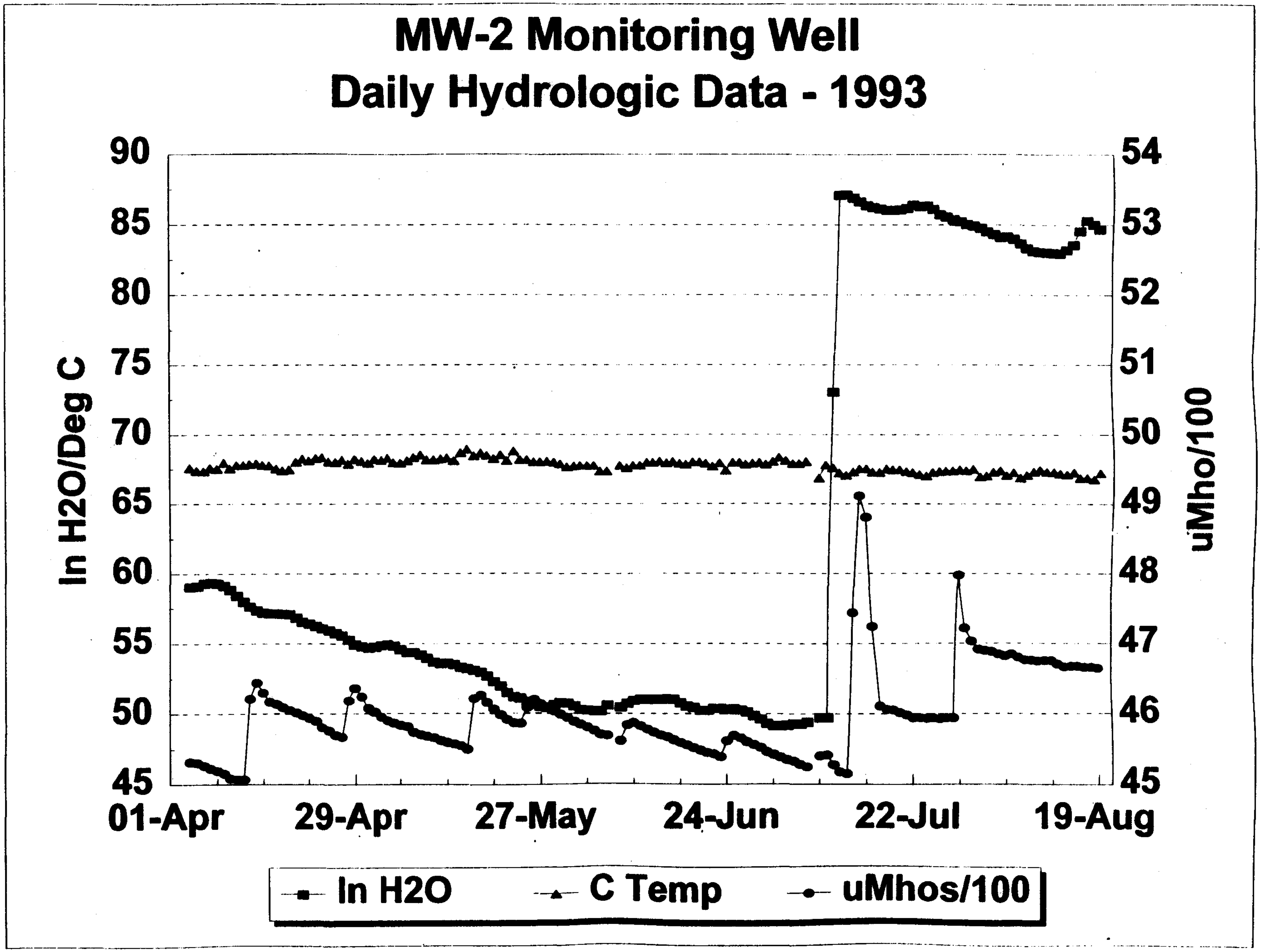
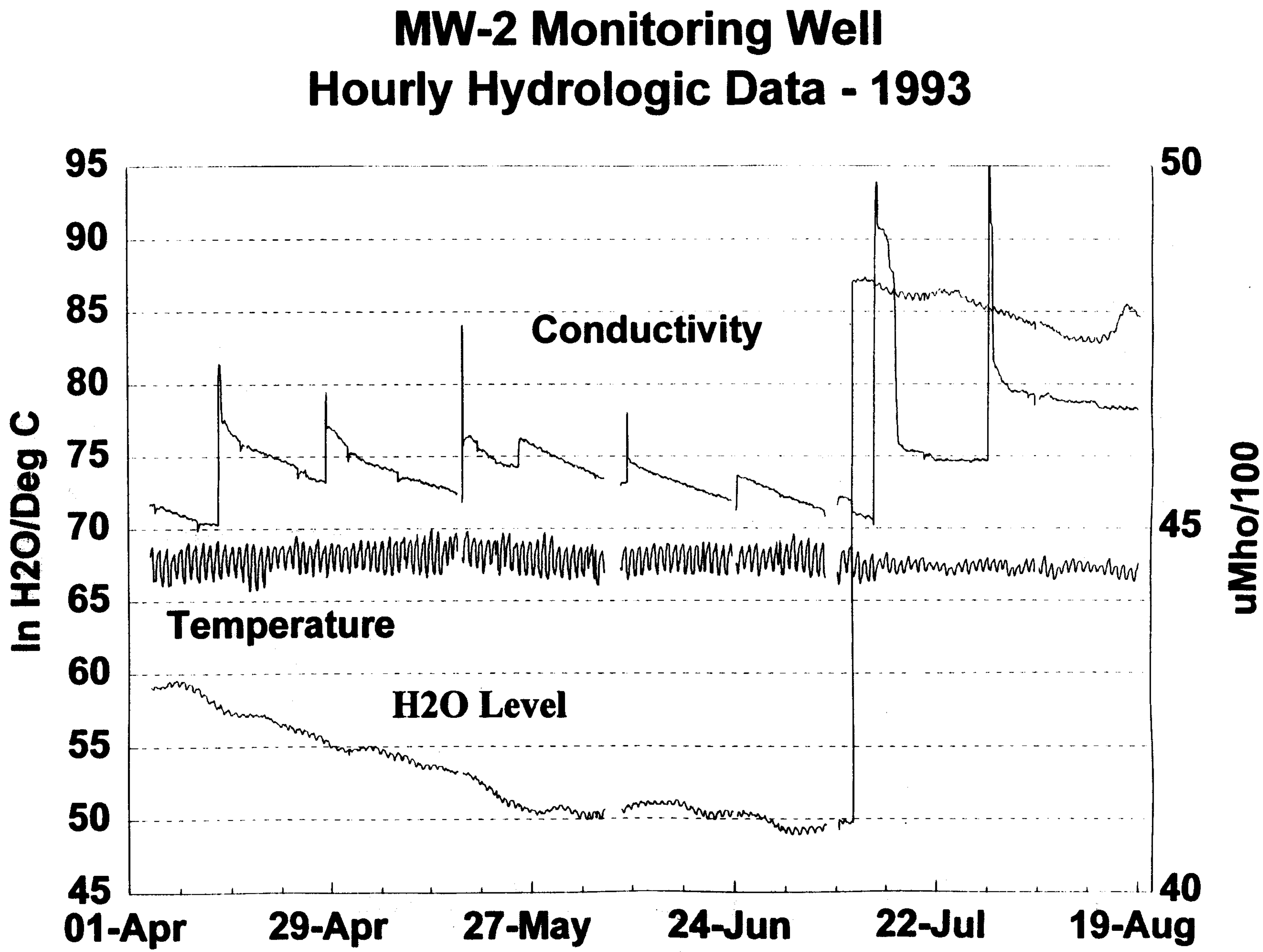

MW-2 Monitoring Well
Daily Hydrologic Data - 1993
90
85
80
75
70
65
60
55
50
45
54
53
52
51
50
49
48
47
46
45
In H2O/Deg C
uMho/100
01-Apr
29-Apr
27-May
24-Jun
22-Jul
19-Aug
In H2O
C Temp
uMhos/100

Figure 12

this time. In early July the instrument package was lowered by an additional 40" in the well in an effort to better contact the groundwater column outside the well; after relocation, the water level shows a continued decline by another five inches. The average water level change of 38 cm (15in) is substantially larger than that seen at the Paradise Park or Malama Ki wells which have respective water level changes of about 20 cm and 13 cm (8in. and 5in.) during this interval (Table 2). Hence, the MW-2 well seems to be more sensitive to changes in groundwater recharge than either of the wells outside the rift zone. Water temperatures average about 68°C, making this well the second hottest shallow well (after GTW-3) in the KERZ, and are seen to rise by only about 3°C during the monitoring interval of April 1 through July 1; relocation of the instruments to a greater depth in the well shows a 2°C temperature drop with only about a 1°C variation during the remainder of the monitoring effort.

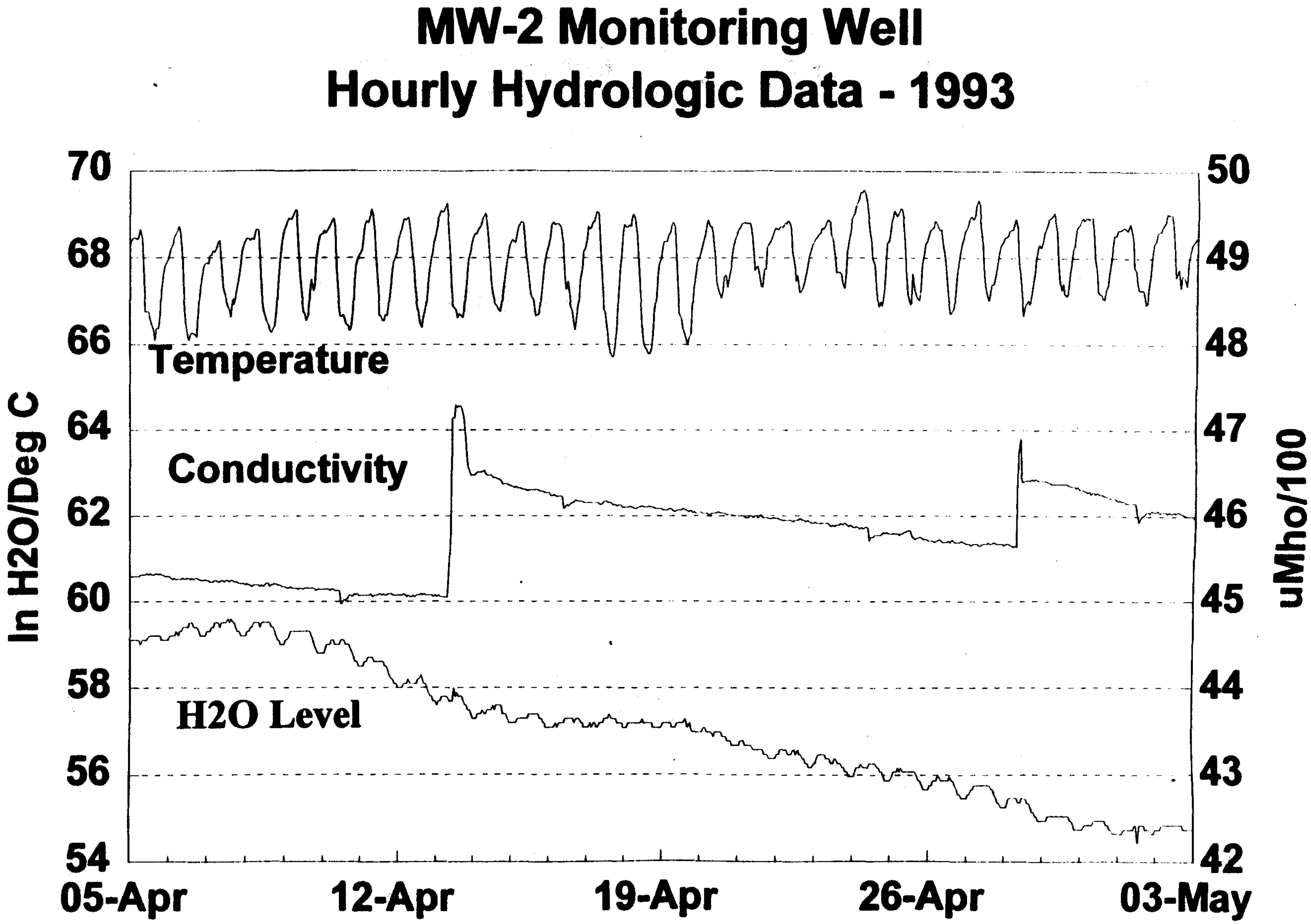
The average conductivity of the water in the well is intermediate between that of Paradise Park and Malama Ki and indicates a salinity that is higher than that of PPW but lower than MKW. Also evident in the conductivity data are a series of short-term jumps that do not correlate well with identifiable changes in temperature or water level. The more detailed hourly data (Figure 13) show that these changes have the appearance of step increases followed by gradual decay toward a baseline value. During the course of the program, it became apparent that these changes were coincident with the two week interval of sample collection from the well. Further investigation of the details of the well completion program found that there was an error in the well design drawings and that the perforated interval of the well casing began 4.5 m (15 ft.) below the water table. Hence, the monitoring instruments were not sampling from the surface of the basal lens in this area but were monitoring a stagnant surface layer in the well. In an effort to alleviate this problem, we lowered the instruments into the well by an additional 30" which was the extent of our available cable. Although this did result in a higher conductivity water being withdrawn during sampling, it is apparent that we were unable to reach the actively mixed layer in the well.

In spite of the difficulties with the location of the instruments in the well, the short-term temperature and water level data show significant diurnal variations: water levels vary by about 1 cm (0.5in.) on a daily basis and temperature by about 3°C. The water level variations



MW-2 Monitoring Well
Hourly Hydrologic Data - 1993
95
90
85
80
75
70
65
60
55
50
45
In H2O/Deg C
50
45
40
uMho/100
Conductivity
Temperature
H2O Level
01-Apr
29-Apr
27-May
24-Jun
22-Jul
19-Aug

Figure 13



MW-2 Monitoring Well
Hourly Hydrologic Data - 1993
70
68
66
64
62
60
58
56
54
50
49
48
47
46
45
44
43
42
In H2O/Deg C
uMho/100
Temperature
Conductivity
H2O Level
05-Apr
12-Apr
19-Apr
26-Apr
03-May

Figure 14

associated with tidal forcing are substantially smaller here than they are at either the PPW or at MKW which showed variations of about 20 cm and 30 cm (8in. and 12in.) respectively. This well is located at a greater distance from the coast line and, hence, would be expected to show a smaller influence from the ocean tides. However, the reduction in tidal influence is more than would be anticipated to arise from this factor alone; a reduction in permeability associated with the rift zone dike complex, isolating the region around MW-2 from the basal groundwater system to the south, may account for the reduced tidal influence. The short-term temperature and water level data also show that the basal groundwater is stratified in this area with warmer water overlying cooler water below. A temperature log has not been conducted for this well under our program and, hence, we don't have an estimate of the thickness of the warm water lens in this area.

The hydrologic monitoring data for MW-2 suggest the following:

1) The basal groundwater system in this area receives a substantial contribution of geothermal fluids discharged from the underlying hydrothermal reservoir;

2) The large changes in water levels seen in response to rainfall recharge and the small tidal response of the water levels is consistent with a groundwater system that is partially confined within the dike system of the KERZ and, to some degree, isolated from the shallow groundwater system to the south.

GTW-3

Geothermal Test Well 3 is located approximately 2 km east north east of the geothermal production and reinjection field that is currently under development. It is down-rift of the development and may be down the hydrologic gradient from the field and, hence, may show some effect of fluid withdrawal or reinjection associated with the PGV wellfield. This well also has the highest water temperature (96°C) of any shallow well in the KERZ and, therefore shows the most direct connection of any of the shallow wells to the underlying geothermal reservoir in the rift.

Our efforts to obtain hydrologic data from Geothermal Test Well 3 (GTW-3) were the least successful of any well attempted in the present study. We initially installed a monitoring array in GTW-3 in August 1992. In spite of the manufacturers assurances that the equipment was capable of operating at temperatures of more than 100°C, as soon as the instruments were installed in the well, they generated erratic and unrealistic results for all parameters being monitored. The instruments were left in the hole for a period that was long enough to demonstrate that their initial response was not the result of transients associated with equilibration of the devices to the conditions within the well and then retrieved and returned to the manufacturer for re-design and fabrication of new instruments that were hardened for high temperature service. The re-designed and re-fabricated instruments were returned after several months and were again deployed in GTW-3 in May, 1993. The second deployment also included the installation of an air-driven bladder pump to allow sampling to be conducted concurrently with the monitoring effort. Although the instruments initially gave reasonable numbers for water level, temperature, and conductivity, within a matter of days the data quality again deteriorated to the point that no useful information was being generated. After failure of the sampling pump in July the instruments were retrieved and were subsequently returned to the manufacturer for repair.

From an operational standpoint, the instruments are not considered to be capable of withstanding the near-boiling conditions present in GTW-3. Although the manufacturer has repeatedly claimed that instruments of the same design have been successfully used in higher temperature wells in other geothermal fields, our experience in Puna has indicated that this equipment has had a reasonable reliability only for ambient temperature wells but a progressively shortened life at increasing temperatures. A second factor contributing to the difficulty in obtaining data from this well were the challenges associated with deployment and recovery of the pump and instrument package to the water table at a depth of five hundred fifty feet. Although we did not lose the equipment in the hole, its installation and recovery required extraordinary effort and again resulted in damage to the instrument cables. The monitoring equipment has been returned to the manufacturer for repair but will not be redeployed in this well. We are currently refurbishing other equipment that will allow us to obtain periodic (monthly) measurement of temperature and water level in the well accompanied by sampling and analysis of the water chemistry at a somewhat lesser interval.

Kapoho Airstrip Well

The Kapoho Airstrip Well (KAW) is located 5 km east northeast of the production and injection field currently under development. The well is in a shallow graben that has a strike parallel to that of the rift zone and recent drilling in the nearby SOH-2 well has demonstrated that deep subsurface temperatures in this area are at least as high as those in the development area.

Groundwater monitoring instruments were initially installed in KAW in May, 1992. The instruments generally worked well for most of the year although in early December, water level readings began to rise sharply and continued to rise through early 1993 to levels that were clearly not realistic. The instruments were removed in March, sent back to the manufacturer for repair, and returned and reinstalled in late May. Although water level and conductivity instruments worked well for the remainder of the year, the temperature sensor failed within a month of re-installation. The instruments were removed from KAW in January, 1994 when the downhole bladder pump failed and was removed for repair.

The instrument operation as this site was substantially better than that at most of the other sites in the rift system but is still considered to be less than optimal. None-the-less, the data clearly show a great deal about the dynamics of the groundwater system in this area and provides a baseline with which to judge future changes in groundwater quality. The daily average temperatures measured for the groundwater at this site (Figures 15 through 17) range between 35°C and 37°C and indicate a modest contribution of thermal water to the local basal lens. Conductivity ranges between 2400 uMhos and 2800 uMhos which places it above that at Paradise Park but well below the Malama Ki and MW-2 wells. These values also show significant variations in response to changes in water level (and recharge). During the first three months of operation (Figure 15), the groundwater levels are seen to progressively decline whereas conductivity increases slowly and temperatures vary only modestly and in no particular direction. In August, water levels begin to trend upward, in response to increased rainfall beginning in late July, and temperatures show a corresponding decline. Surprisingly, the conductivity shows a significant increase as well which is contrary to what has been observed with most other wells in the rift. The increased conductivity gradually decays over a period of about two months and returns to its pre-increase levels by early October. In November, the rate of increase in water levels accelerates in response to heavy rainfall during that month and,

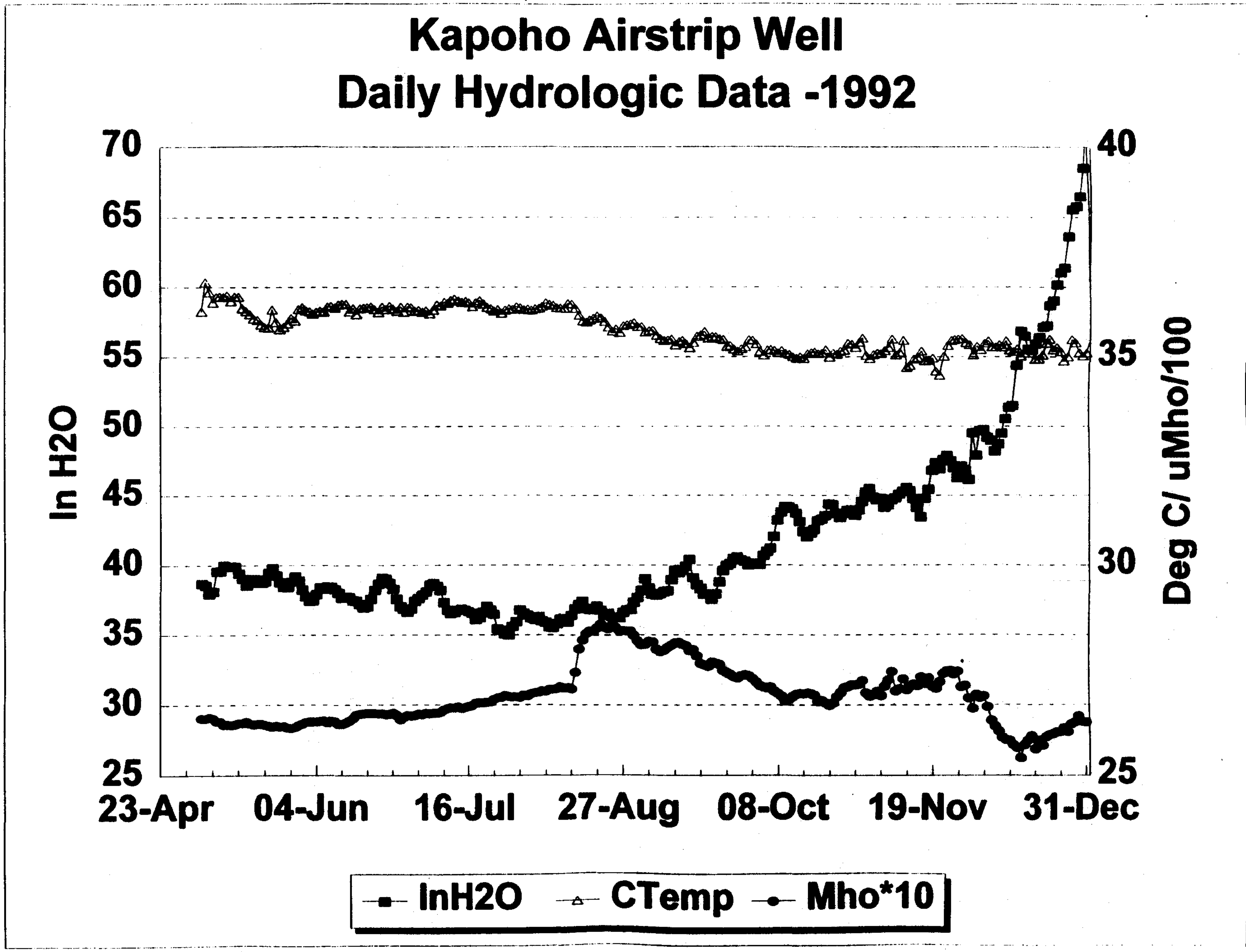

Kapoho Airstrip Well
Daily Hydrologic Data -1992
70
65
60
55
50
45
40
35
30
25
In H2O
40
35
30
25
Deg C/ uMho/100
23-Apr
04-Jun
16-Jul
27-Aug
08-Oct
19-Nov
31-Dec
InH2O
CTemp
Mho*10

Figure 15

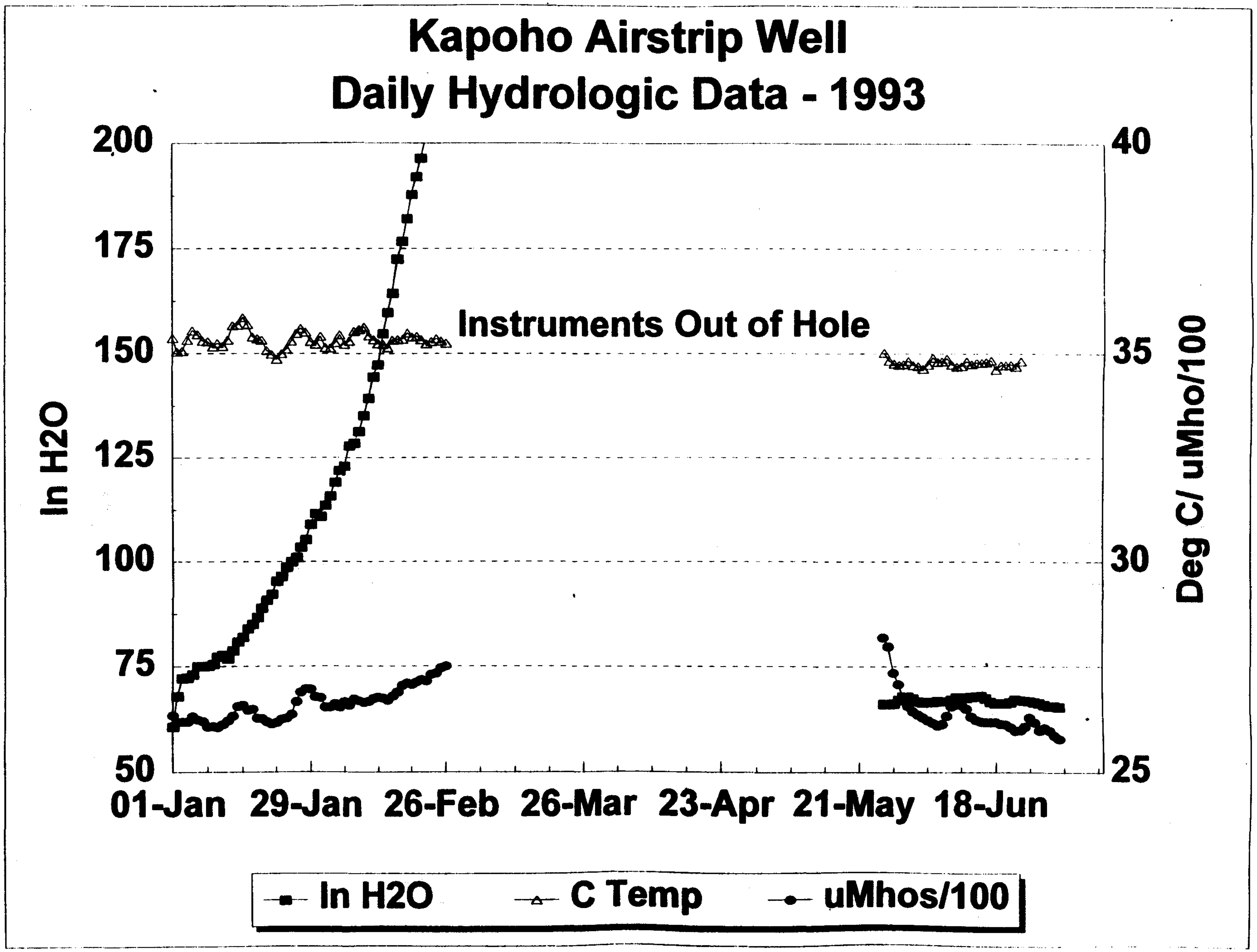
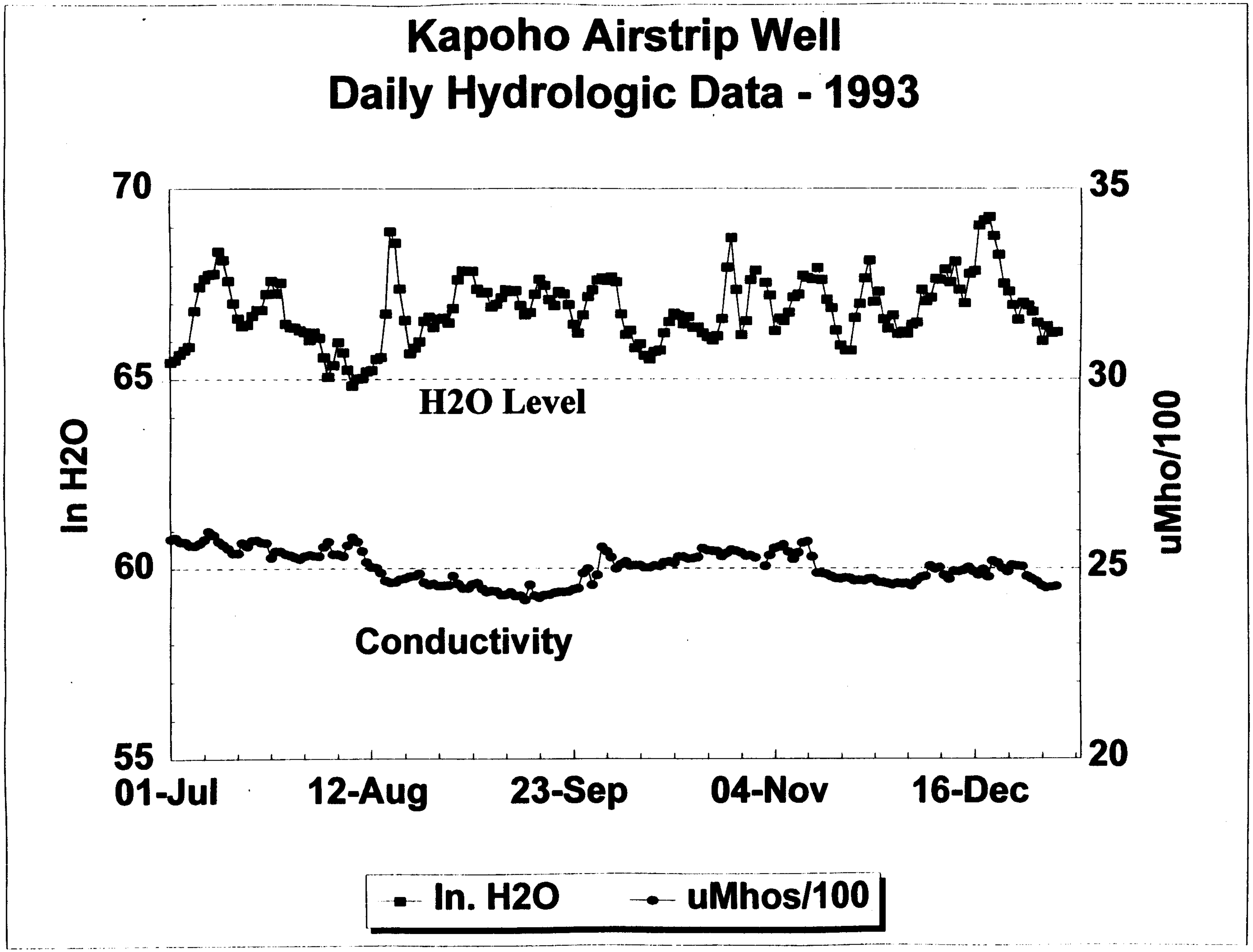

Kapoho Airstrip Well
Daily Hydrologic Data - 1993
Instruments Out of Hole
In H2O
Deg C/ uMho/100
200
175
150
125
100
75
50
40
35
30
25
01-Jan
29-Jan
26-Feb
26-Mar
23-Apr
21-May
18-Jun
In H2O
C Temp
uMhos/100

Figure 16


Kapoho Airstrip Well
Daily Hydrologic Data - 1993
70
65
60
55
35
30
25
20
In H2O
uMho/100
H2O Level
Conductivity
01-Jul
12-Aug
23-Sep
04-Nov
16-Dec
In. H2O
uMhos/100

Figue 17

whereas temperature shows no clear change, conductivity shows a rapid drop. For the following three months, temperature holds steady but conductivity gradually recovers to its pre-rainfall levels. Although the loss of data during the early part of 1993 limits the usefulness of that monitoring interval, the latter half of the year shows several interesting characteristics: in mid-July, two episodes of increased water levels brought increases in conductivity whereas in mid-August, increased water levels results in lower conductivity.

The hourly groundwater data (Figures 18 and 19) shows a substantial tidal signal in the groundwater levels, approximately equivalent to that seen in the Malama Ki well, which suggests that the shallow basal system is not isolated from the ocean to the degree that the MW-2 well is. These data also show that the groundwater is stratified with warmer and more saline water at the surface and cooler water below. The hourly data for the conductivity spike in August, 1992 (Figure 20) also shows an interesting correspondence with the groundwater temperature: the increase in conductivity is accompanied by an increase in the short-term variability of the water temperature. This is interpreted to indicate that a mixing event may have produced the conductivity spike which resulted in both a higher salinity in the water as well as an increase in stratification of the water column. It is postulated that the increase in rainfall uprift may have resulted in increasing water levels and spillover of water from another dike confined compartment that moved downrift through this portion of the basal lens. It is noted that the increases in water level that were accompanied by increases in conductivity during the monitoring interval were more frequently of a longer duration (longer wavelength) whereas those that were accompanied by decreases in conductivity were shorter in duration (e.g. the early August, 1993 event). This suggests that the latter were local recharge events whereas the former are associated with migration of groundwater down, or across, the rift axis. Further analysis and modelling of the rainfall and water level data will have to be conducted to fully develop the dynamics of this process.

In summary, the groundwater data for the KAW well shows that:

1) There is a complex set of interactions between rainfall and groundwater response in this area;
2) The basal groundwater system is in close hydraulic communication with the ocean;
3) The groundwater is mixed with a moderate contribution of natural geothermal discharges; and

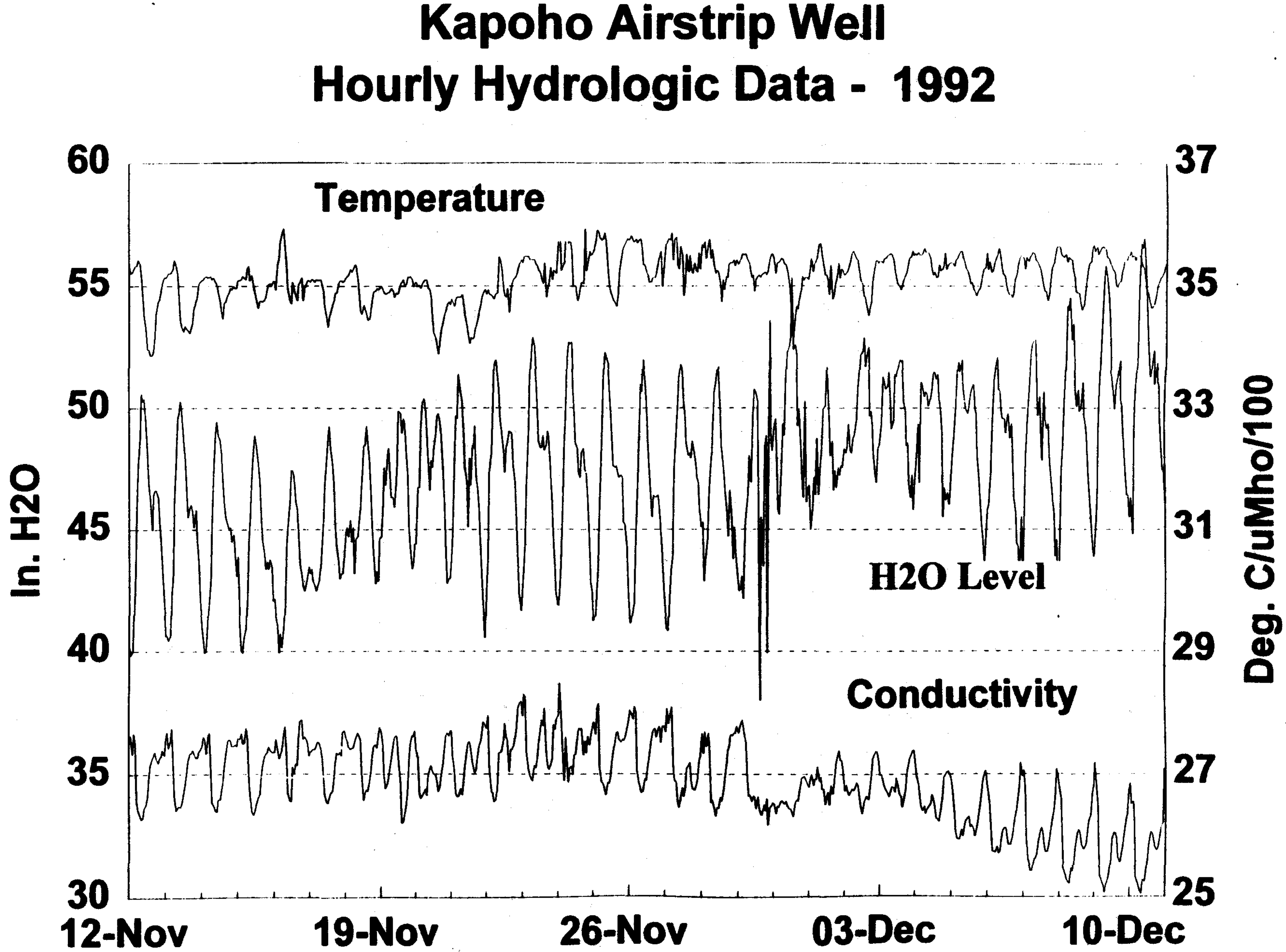
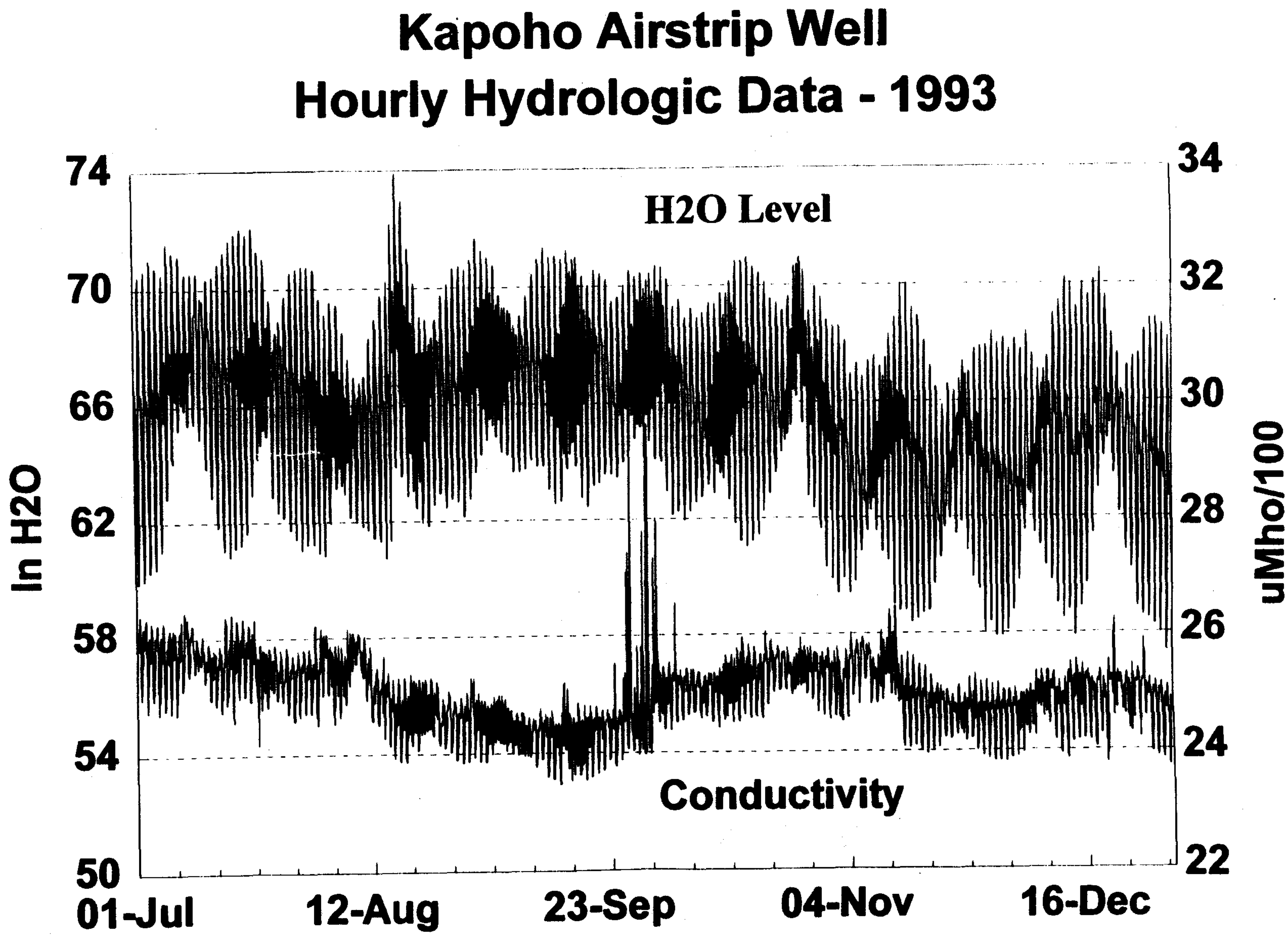
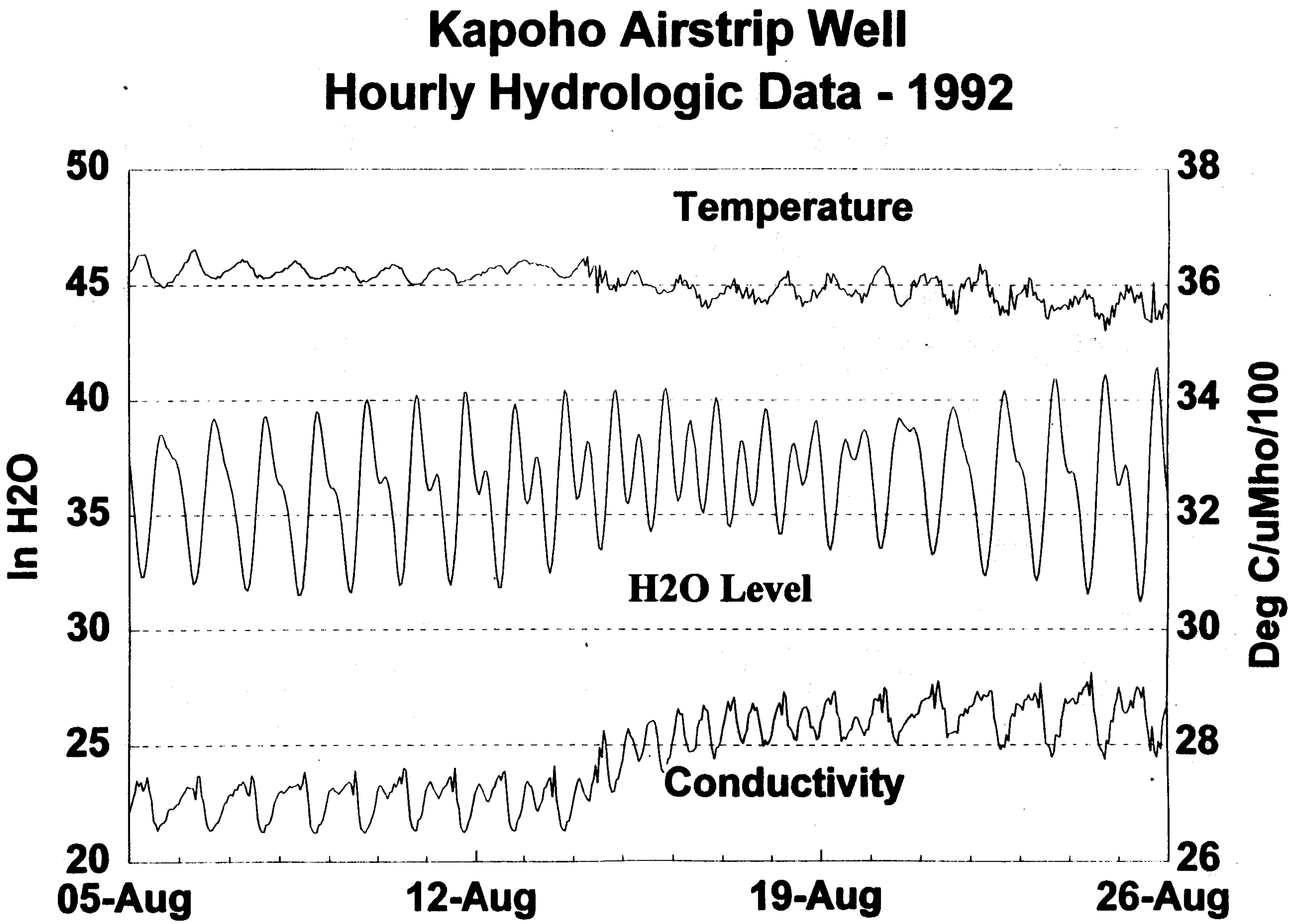

Kapoho Airstrip Well
Hourly Hydrologic Data - 1992
Temperature
H2O Level
Conductivity
In. H2O
Deg. C/uMho/100
60
55
50
45
40
35
30
37
35
33
31
29
27
25
12-Nov
19-Nov
26-Nov
03-Dec
10-Dec

Figure 18



Kapoho Airstrip Well
Hourly Hydrologic Data - 1993
H2O Level
Conductivity
In H2O
uMho/100
74
70
66
62
58
54
50
34
32
30
28
26
24
22
01-Jul
12-Aug
23-Sep
04-Nov
16-Dec

Figue 19



Kapoho Airstrip Well
Hourly Hydrologic Data - 1992
Temperature
H2O Level
Conductivity
In H2O
Deg C/uMho/100
50
45
40
35
30
25
20
38
36
34
32
30
28
26
05-Aug
12-Aug
19-Aug
26-Aug

Figure 20

4) The basal groundwater system is stratified with warmer, more saline waters at the top and cooler, less saline waters below.

Allison Well

The Allison well is located south of the KERZ and is downgradient of the area currently under development. It has been considered a prime candidate for monitoring for any changes in discharge from the rift that might arise from the development activities but, until recently, the presence of a defunct water pump in the well has precluded access. After an extended negotiation with the landowner regarding access to the well, a small workover rig was brought in to the site in late September, 1993 and the pump and water tubing were removed from the well. A set of monitoring instruments and a downhole pump were installed in the well in November and data is currently being obtained from this array.

Although the monitoring interval at this site is relatively short, the general characteristics of the groundwater system are evident in the currently available data set (Figures 21 and 22). Groundwater temperatures average slightly less than 37°C and show a strong response to rainfall events with changes of as much as 1.5°C after rainfalls in late December 1993 and mid February 1994. Daily average groundwater levels show a subdued response to rainfall recharge with changes in water level of less than 13cm (5 in.) for any of the events recorded to date. The conductivity data appears to be unique among the wells that have been monitored in Puna: daily average values appear to cycle from 500 uMhos to a saturation value (off scale and not shown in Figure 21) and then abruptly drop to low values with each rainfall only to steadily rise again to a saturation value. This response is believed to be the result of a water-based lubricant put into the well during the removal the downhole pump. Although this material does not pose an environmental threat, it strongly affects the viscosity (and apparently conductivity characteristics) of the water and tends to dissipate slowly. Until this material is flushed from the well, the conductivity data will have to remain suspect and any interpretation of the data would not be warranted.

The hourly data shows that tidal effects strongly influence water levels at this site with maximum variations in water level exceeding 30". Temperature changes in response to the tidal flux are much more subdued than those seen at most of the other wells in the region with a

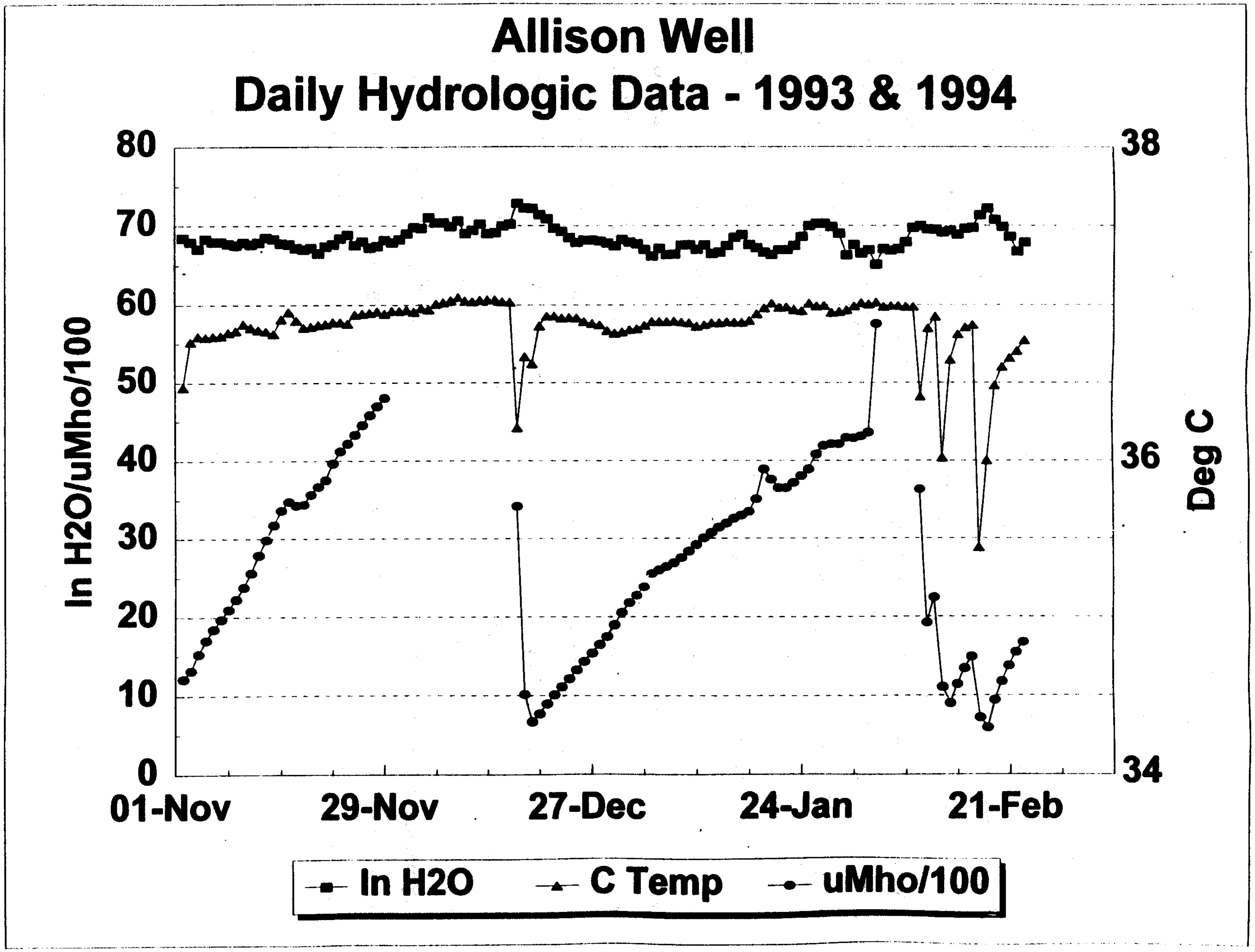

Allison Well
Daily Hydrologic Data - 1993 & 1994
80
70
60
50
40
30
20
10
0
In H2O/uMho/100
38
36
34
Deg C
01-Nov
29-Nov
27-Dec
24-Jan
21-Feb
In H2O
C Temp
uMho/100

Figure 21

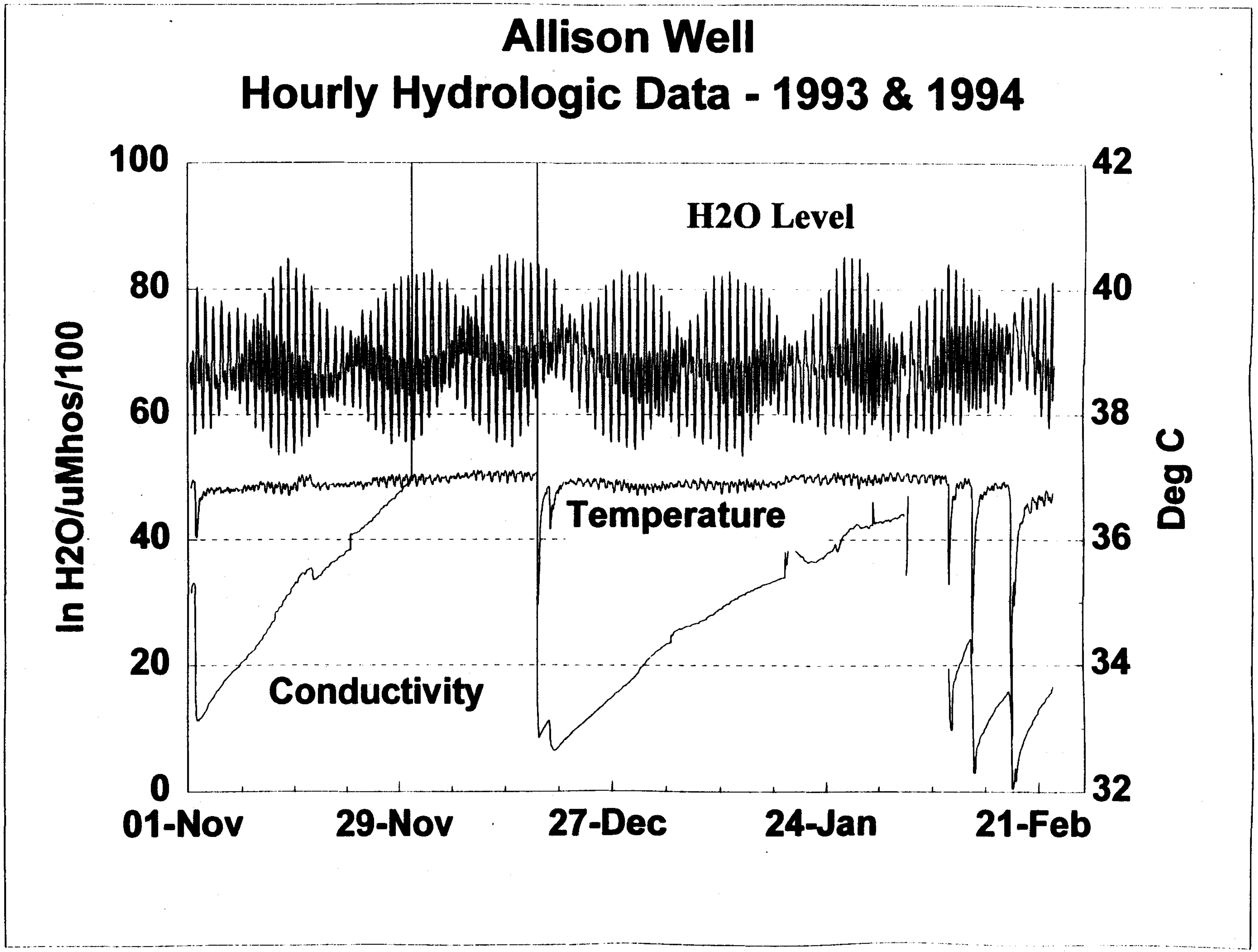

Allison Well
Hourly Hydrologic Data - 1993 & 1994
H2O Level
Temperature
Conductivity
In H2O/uMhos/100
Deg C
100
80
60
40
20
0
42
40
38
36
34
32
01-Nov
29-Nov
27-Dec
24-Jan
21-Feb

Figure 22

change of only about 0.25°C for a 20" change in water level thus indicating that the groundwaters are better mixed than those within the rift zone. The temperature response to rainfall recharge is also apparent in the hourly data and shows an even stronger response than that seen in the daily averages: temperatures fall by about 4°C with the strong rainfall event in mid-February 1994.

In summary, the data for this site show that there is a strong tidal response, and high tidal efficiency, for the basal lens at this location and that there is a significant contribution of geothermal fluids in the groundwater here. The temperature response to changing water levels suggests that the water is not highly stratified (well mixed) and, hence, that the source of geothermal fluids is located at some distance from this well.

Discussion of Monitoring Results

A summary of the general characteristics of each well's monitoring data are presented in Table 2. Although each well exhibits a unique set of conditions, there are a few distinguishing features that allow them to be classified into identifiable groups. The wells located outside the rift zone, Paradise Park, Malama Ki and Allison, show modest changes in water level in response to seasonal variations in rainfall whereas those inside the rift zone, MW-2 and KAW, show substantially larger changes due to rainfall recharge. Clearly, those wells located within and south of the rift contain substantial contributions of geothermal fluid to the basal water table. The diurnal variations in temperature and conductivity in all the wells but Allison well strongly indicate that the water in the basal lens within and close to the rift is stratified. Although the degree of stratification in MW-2 is difficult to assess since the well does not sample the top of the water table, it is evident that there is less stratification in the Kapoho Airstrip Well than there is in the Malama Ki well: for nearly the same diurnal water level fluctuation, the temperature and conductivity variations in KAW and Allison are less than half those in MKW. In very general terms, this suggests that the source for the hot water at KAW is probably more distant from that well than is the source of the thermal fluids that feed the MKW.

The temperature and conductivity of the water in the wells within and south of the rift zone show a moderate to strong sensitivity to changes in rainfall. The typical, and more expected result, is that an increase in rainfall generates a rapid decrease in temperature and conductivity as the rainfall recharge mixes with and dilutes the thermal fluids at the surface of the basal lens.

Although this process was observed at Malama Ki, the Kapoho Airstrip Well showed both increases and decreases in conductivity in response to rainfall depending on whether the rainfall occurred locally or up-gradient of the well. In the latter case, apparent spillover of more saline water produced an increase in salinity (conductivity) at KAW rather than the expected decrease.

With respect to the application of the continuous groundwater data to compliance monitoring of PGV activities, at least two conclusions can be offered:

1) The temperature, conductivity, and water level data presently in hand do not indicate that there has been a detectable adverse impact on the groundwater quality that can be attributed to the production or reinjection activities that are occurring in the PGV production field. We have not seen any clear-cut trends in salinities or temperatures that are indicative of a change in the rate of natural discharge of geothermal fluids to the shallow basal system.

2) An equally important conclusion drawn from the currently available data is that the temperature and chemical composition of the basal groundwaters vary with seasonal changes in rainfall, and on a daily basis in response to recharge events. Hence, periodic sampling of the basal groundwater in these wells is expected to show substantial variations in chemical composition and temperature in response to changes in rainfall recharge. Stratification of the water in the basal lens, along with tidal variations in water levels add further to the variability to the apparent groundwater compositions determined by periodic sampling of the basal waters.

III. Groundwater Chemistry Program

The second major effort within the monitoring program consisted of periodic sampling of the basal groundwaters for detailed chemical analysis. The planned procedure for this effort was to obtain samples from the monitored wells through the use of an air driven bladder pump installed in the wells with the monitoring array. A number of other wells in sampling array are used for municipal or utility water supplies and already have permanently installed pumps in them; these wells were sampled at the pump discharge. Those wells that had no installed pump were sampled using a Teflon or stainless steel bailer.

With respect to the air driven sample pumps, the operational response was mixed. In some instances, the pumps worked well for extended periods of time and consistent samples were recovered on a routine basis with few difficulties. In other cases, however, a variety of operational problems led to premature failure of the pumps and required their removal for servicing. These problems ranged from corrosion debris accumulation in the pump inlet at Malama Ki and the Kapoho Airstrip Well to the failure of the pump bladder in MW-2 and GTW-3. The former malfunction was rectified by a revision to the pump configuration in the well that made it less susceptible to accumulation of debris at the pump intake. Failure of the pump bladder appears to be a less tractable problem. For most of the market served by these pumps, the typical installation conditions consist of emplacement to depth of about 30 m (100 ft.) or less below the ground surface and exposure to groundwater temperatures are less than 25°C. In the present installation, the pumps appear to be at, and in some cases beyond, their intended design conditions. None-the-less, they are the only pumps that were found that were expected to be able to function at all under the difficult field conditions in Puna. We are presently working on modifying the design of the pumps in an effort to eliminate the need for an internal bladder that will still provide us with the capability of returning water samples from depth using compressed air as a driving mechanism.

Geochemistry Results

The wells for which detailed analyses of the water chemistry were conducted included all those in which instruments were installed as well as several others for which continuous monitoring was either infeasible or not justified by their location. The wells monitored and the average concentrations of their major ions are presented in Table 3 and Figure 23. The order of presentation in the table is generally from a northerly direction toward the south across the axis of the rift zone; Figures 24 and 25 present the data in the same fashion. As is evident from the average ion concentrations, the levels of dissolved solids increases from north to south reflecting the progressively larger contribution of dissolved solids injected into the basal groundwater system by natural geothermal discharge from the rift zone. There are, however, some obvious excursions away from this trend:

1) GTW-3 shows the highest concentrations of dissolved ions, and the highest temperature, of the wells in the survey area and samples the basal lens in close proximity to a naturally occurring source of geothermal fluids being discharged into the groundwater system;

TABLE III
Average Concentrations and Coefficients of Variation for Puna Groundwater

		Na	K	Mg	Ca	Cl	SO_4	HCO_3	SiO_2	pH
Paradise Park	Mean Value	14.5	2.8	2.5	3.1	9.5	4	40.7	61.8	7.3
Pahoa	Mean Value	16.5	2.6	3.5	5.1	11.7	11.4	39.8	55.9	7.8
	Coeff. Variation	5.8	23	3.5	5	25.6	14.4	3.9	6.2	
Kapoho Airstrip	Mean Value	266	17.5	27.3	36.5	474	166	32.8	83.9	7.5
	Coeff. Variation	17.4	18.4	12.7	12.8	17.3	4	681	9.5	
Kapoho Shaft	Mean Value	1002	6.9	33.8	55.6	149	17.9	290	55.8	7.7
	Coeff. Variation	14	17.2	7.8	3.6	20.2	16.2	2.2	6.7	
MW-1	Mean Value	60.8	12.3	12	21.5	20.5	192	28.2	102	6.3
	Coeff. Variation	12.1	53.5	7.9	9.1	20	19	18	10.3	
MW-3	Mean Value	64.5	12.2	12.5	22.3	26.6	188	24.2	105	7.3
	Coeff. Variation	6.1	30.4	6.6	5.8	34.3	32.7	25.8	5	
GTW-3	Mean Value	3256	254	182	218	5817	615	28.9	187	7
	Coeff. Variation	14.7	16.8	18	11.2	11.1	34.9	22.6	18.7	
MW-2	Mean Value	595	26.6	16.7	43.4	978	95.4	55	53.6	8
	Coeff. Variation	9.8	11.4	62.9	26	15.8	39.7	18.4	58.1	
Allison Well	Mean Value	145	6.4	12.7	10.2	203	39.4	77	23.3	7.7
	Coeff. Variation	36.5		52.9	48.1	38.9	23	15.6	21.5	
Malama Ki	Mean Value	2898	161	267	167	5445	601	150	159	7.4
	Coeff. Variation	32.8	37.4	36.5	28.5	26.7	21.2	19.7	24.1	

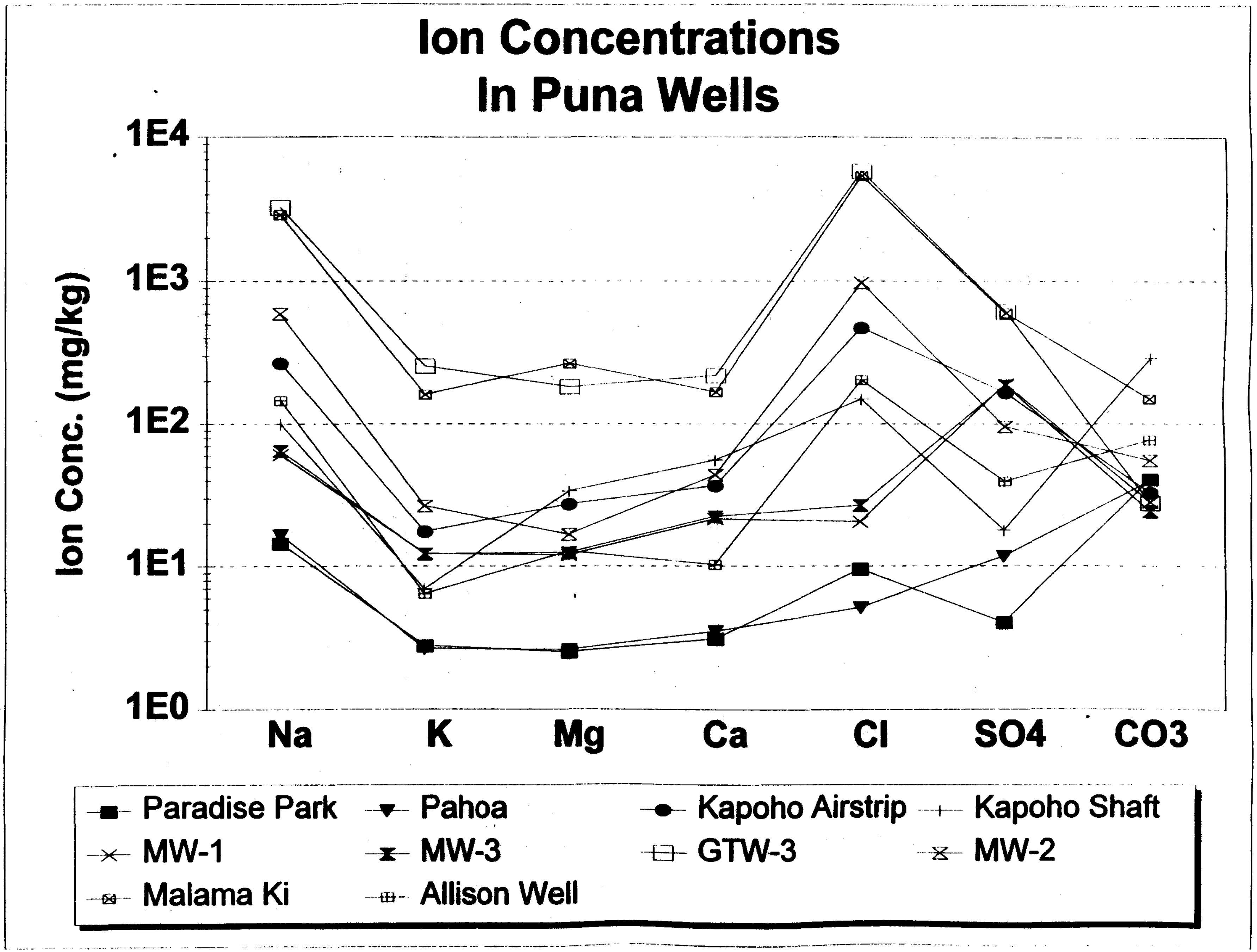

Ion Concentrations
In Puna Wells
1E4
1E3
1E2
1E1
1E0
Ion Conc. (mg/kg)
Na
K
Mg
Ca
Cl
SO4
CO3
Paradise Park
Pahoa
Kapoho Airstrip
Kapoho Shaft
MW-1
MW-3
GTW-3
MW-2
Malama Ki
Allison Well

Figure 23

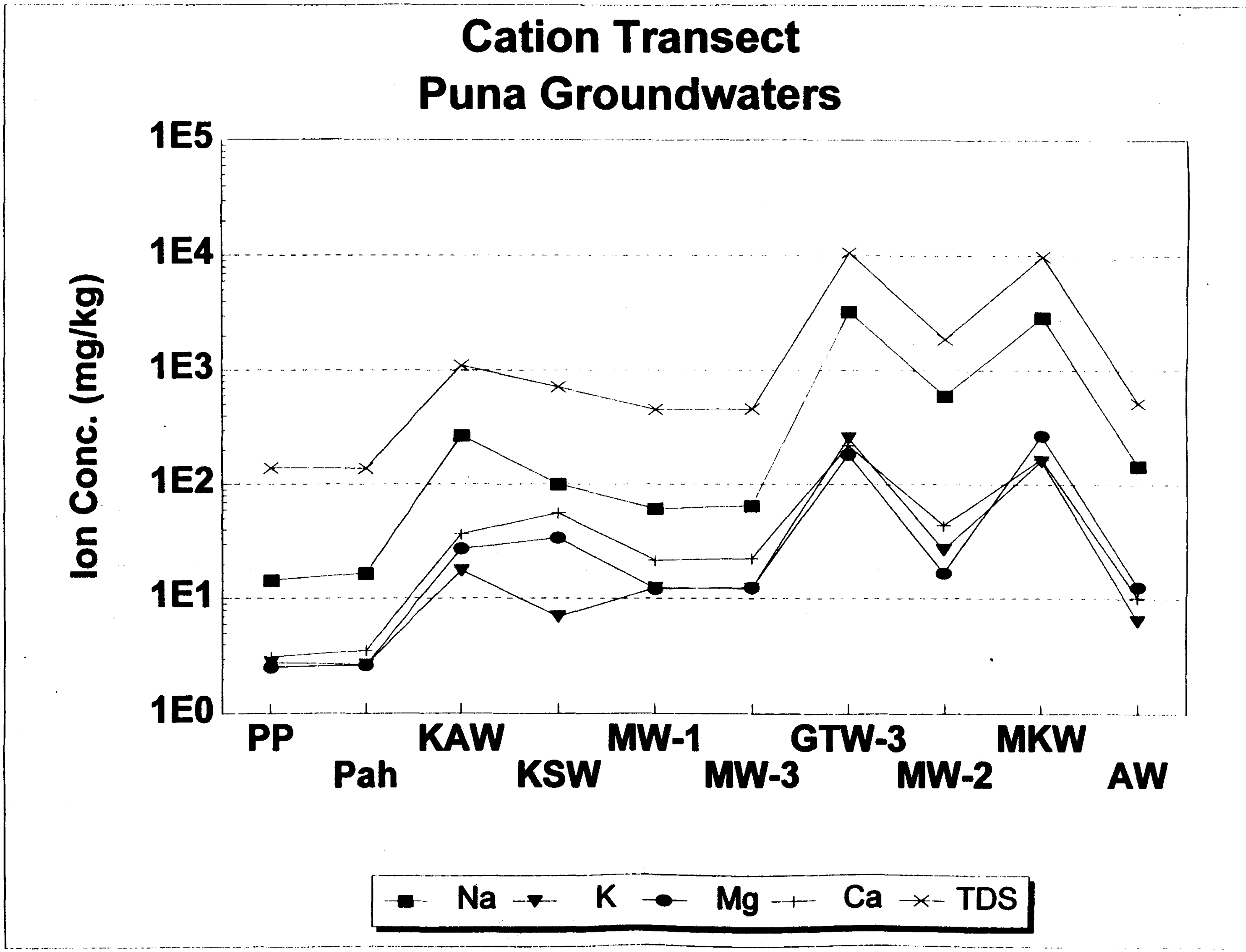

Cation Transect
Puna Groundwaters
1E5
1E4
1E3
1E2
1E1
1E0
Ion Conc. (mg/kg)
PP
Pah
KAW
KSW
MW-1
MW-3
GTW-3
MW-2
MKW
AW
Na
K
Mg
Ca
TDS

Figure 24

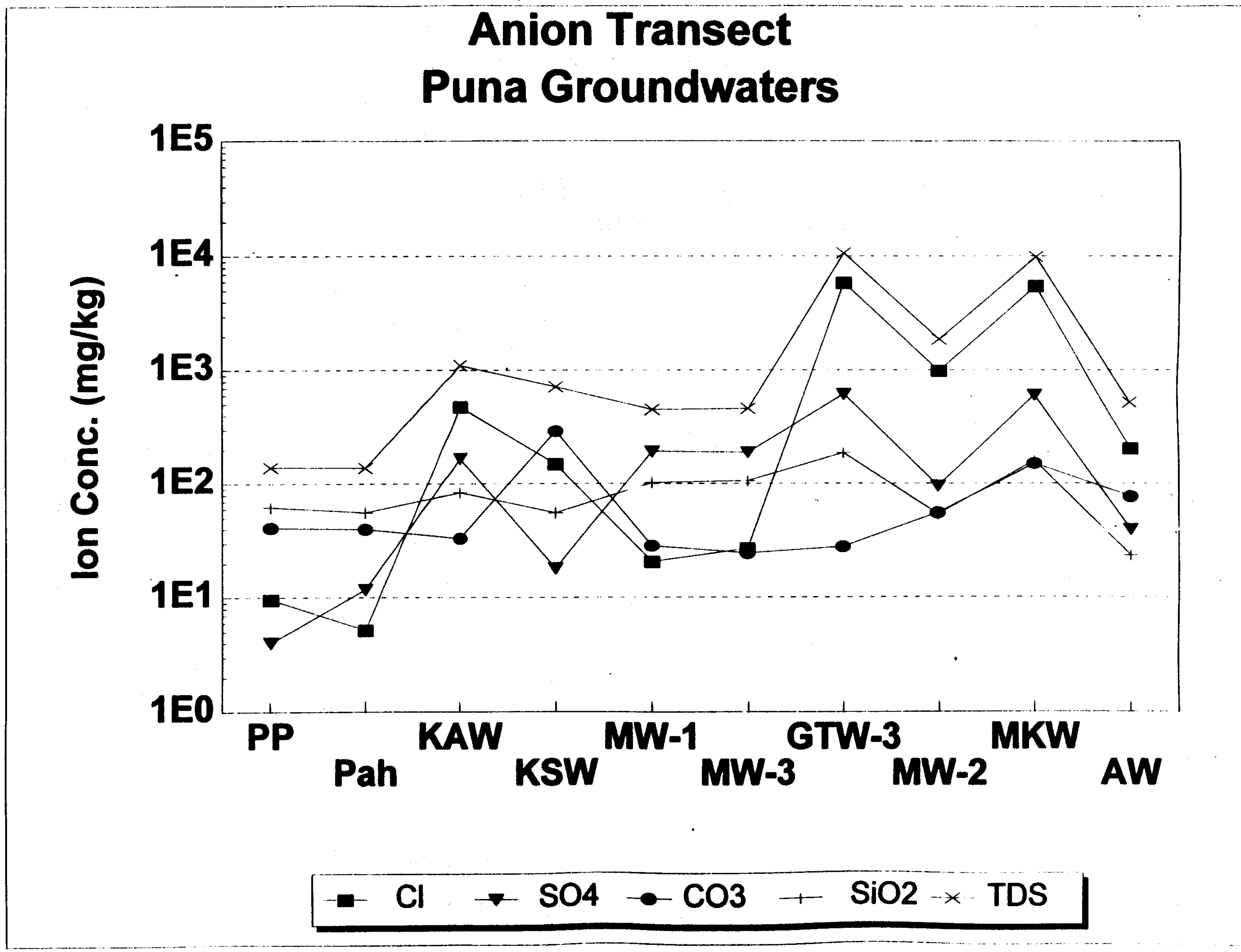

Anion Transect
Puna Groundwaters
1E5
1E4
1E3
1E2
1E1
1E0
Ion Conc. (mg/kg)
PP
Pah
KAW
KSW
MW-1
MW-3
GTW-3
MW-2
MKW
AW
Cl
SO4
CO3
SiO2
TDS

Figure 25

2) The Kapoho Airstrip Well also appears to have a higher concentration of dissolved solids for its location on the rift than do MW-1 and MW-3.

Aside from these deviations, the general trend in the groundwater chemistry indicates that waters north of the rift contain extremely low dissolved solids concentrations and, as the rift zone is approached, the contribution of dissolved solids from naturally occurring discharge of geothermal fluids progressively increases.

Within the overall trend, however, is evidence that the basal groundwater is not a simple mixture of freshwater recharge and seawater or thermally altered seawater discharged by the rift. This is best seen in a plot (Figure 26) of the ion-to-chloride ratios of each groundwater source normalized to a seawater ion-to-chloride ratio ($[Ion/Cl]_{(well\ water)}/[Ion/Cl]_{(seawater)}$). If these waters were simply a mix of seawater and rainfall, the ratios would all be equivalent to unity; if they were mixtures of freshwater and thermally modified seawater, the ratios would deviate from unity but would all form a family of parallel lines in the plot. Figure 26 shows that there are, in fact, two families of curves as well as one water source that belongs to neither family. The upper family of curves corresponds to those groundwaters located north of, or on the northern portion, of the rift zone and have a generally low dissolved solids concentration: PPW, Pahoa Well, MW-1 and MW-3. The lower family of curves corresponds to those wells on the southern portion of, or south of, the rift and have higher dissolved solids concentrations: MW-2, GTW-3, MKW, Allison Well, and the KAW. KSW appears to belong to neither family.

PPW is considered to be our reference well for a basal groundwater unaffected by geothermal discharges. Most of the normalized ion ratios for the upper family of curves parallel those of the PPW and, hence, can be considered to have a similar origin. The sulfate ion ratio in this group does not, however, track that of PPW but appears to show a progressive increase through the Pahoa Well, which has about twice the relative sulfate concentration, to MW-1 and MW-3 with more than ten times the PPW sulfate ratio. The elevated temperatures in MW-1 and MW-3 clearly indicate that some geothermal heating has occurred in the groundwater here. The presence of elevated sulfate concentrations, without a significant elevation in chloride levels, suggests that the basal water has been heated by steam: discharge of hydrogen sulfide bearing steam into the groundwater system, and subsequent oxidation of the sulfide to sulfate, easily

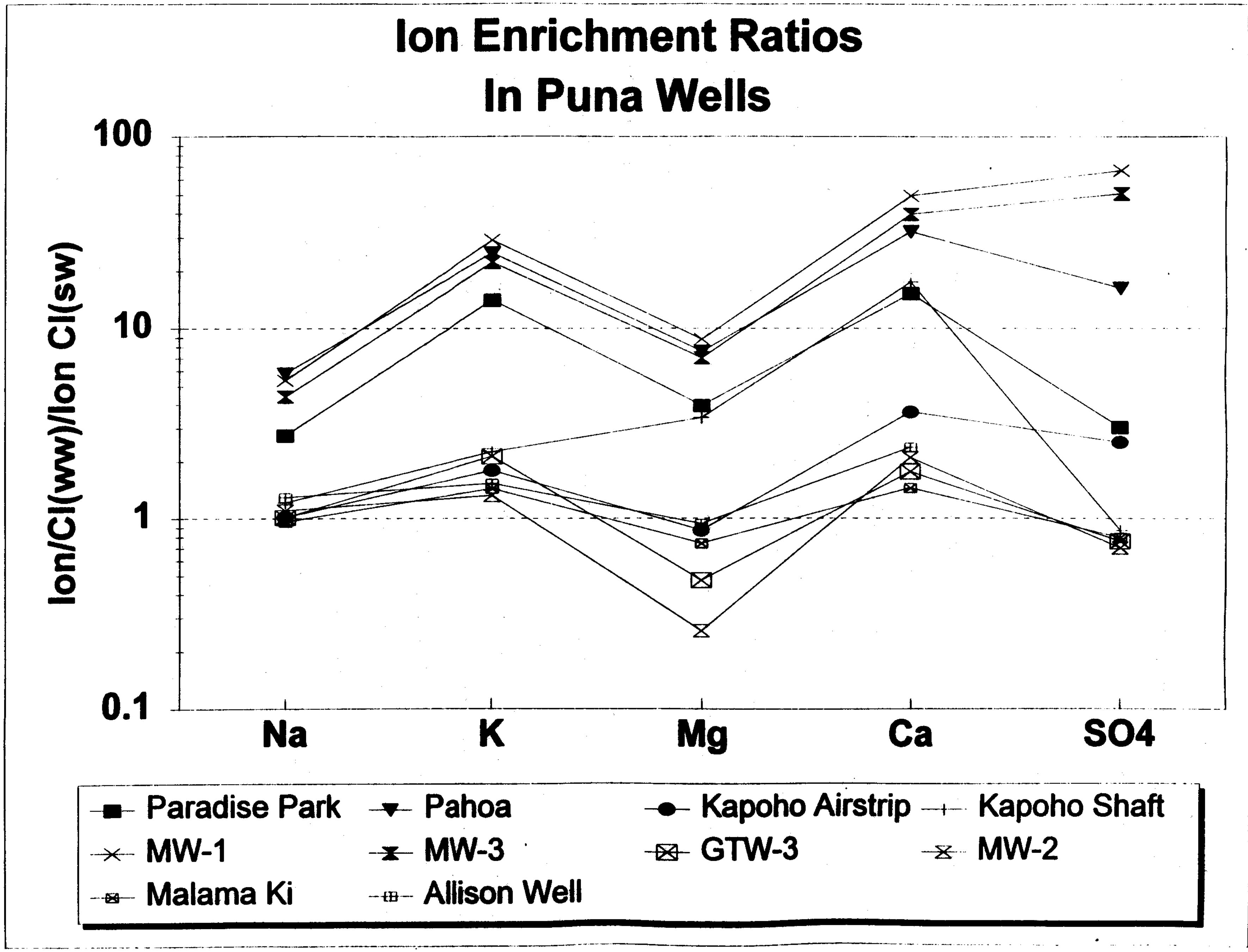

Ion Enrichment Ratios
In Puna Wells
100
10
1
0.1
Ion/Cl(ww)/Ion Cl(sw)
Na
K
Mg
Ca
SO4
Paradise Park
Pahoa
Kapoho Airstrip
Kapoho Shaft
MW-1
MW-3
GTW-3
MW-2
Malama Ki
Allison Well

Figure 26

accounts for both the elevated temperature and selective enrichment of sulfate in these well waters. This further implies that there may be an additional steam zone, similar to that discovered by the KS-8 well, located to the north of the current well field. The more modest elevation of sulfate ratios in the Pahoa Well suggests that a similar source.may exist up-rift of this area; the large flux of groundwater through this area would, however, be expected to dilute whatever geothermal contribution might be present.

The lower family of curves shows ion concentration ratios that are generally consistent with a thermally modified seawater. The compositions of such waters typically show little modification of sodium concentrations, elevated potassium and calcium levels, and depleted magnesium and sulfate concentrations. The elevated ion values generally reflect breakdown of the parent rock into secondary minerals whereas the depleted ions are typically taken up in the formation of high temperature alteration products or deposition of minerals having a retrograde solubility (e.g. calcium sulfate will generally precipitate from heated seawater as anhydrite). Although the ion ratios for the lower curves are not sufficiently different to draw any firm conclusions, their general trend suggests that the saline water present in MW-2 and GTW-3 show the most intense alteration whereas MKW and the Allison Well appear to have less intensively altered seawater than the other two wells in the rift or may have received a larger contribution of unaltered seawater to the upflow of geothermal fluids. It is noted that KAW also shows evidence of an elevated sulfate concentration which may reflect some steam contribution to the increased water temperatures in this well.

It should be noted here that, although the above analysis can give general indications of the degree of alteration of the seawater component, an attempt to calculate the temperatures of the source fluids has not been made. Earlier, and current, studies of the groundwater in Puna have shown that none of these mixed waters have a composition that can be considered to be at equilibrium with the reservoir rocks. In the terminology of other work on geothermal fluids, the groundwaters show immature compositions that have not had time to fully equilibrate with reservoir temperatures.

The Kapoho Shaft well, as noted above, bears little evident relationship to either the fresh groundwaters north of the rift or the thermally altered groundwaters within or south of the rift. Earlier studies have postulated that this well draws from an isolated aquifer fed by rainfall infiltration into Kapoho Crater. The unusual groundwater chemistry arises from interactions between the groundwater and an ash bed that underlies the water body: potassium, magnesium, and calcium are being leached out of the ash and are ion balanced by bicarbonate ion dissolved from the soil gas. Hence, this water system appears to have little interaction with the larger groundwater system within the rift zone.

Time Series Groundwater Data

The primary purpose of our time series sampling of the groundwater in Puna was to document the baseline concentrations of dissolved solids in the groundwater, characterize the changes that occur in the water quality in response to seasonal variations in recharge, and to monitor for any changes that might be the result of the production or reinjection of geothermal fluids in the wellfield currently under development. The discussion that follows will treat the wells from north to south across the rift zone. The data for each well for which analyses have been performed will be presented in graphical form; tables of analytical results are presented in Appendix A.

Pahoa Well

The Pahoa Well is located north of the surface expression of the KERZ and is used as a municipal water well for the town of Pahoa and surrounding communities. As discussed above, it is relatively free of geothermal influence from the rift zone and the chemical composition of its water is expected to reflect seasonal changes in the groundwater system that result from varying amounts of recharge to the basal lens. The time series data presented in Figure 27 show that the basal water in this area contained low concentrations of dissolved solids throughout the monitoring interval. Increases in chloride and sodium concentrations during the summer months of 1993 reflect the effects of lower rainfall recharge rates to the basal water system or increases in pumping of this water source under different rainfall conditions. Because these wells serve a broad area they may have pumping rates up to several hundred thousand gallons of water a day. In general, however, the concentrations of dissolved solids have remained within a relatively narrow range: the coefficient of variation (standard deviation divided by the mean value) expressed as percent, for this well range from about 5% to 20%.

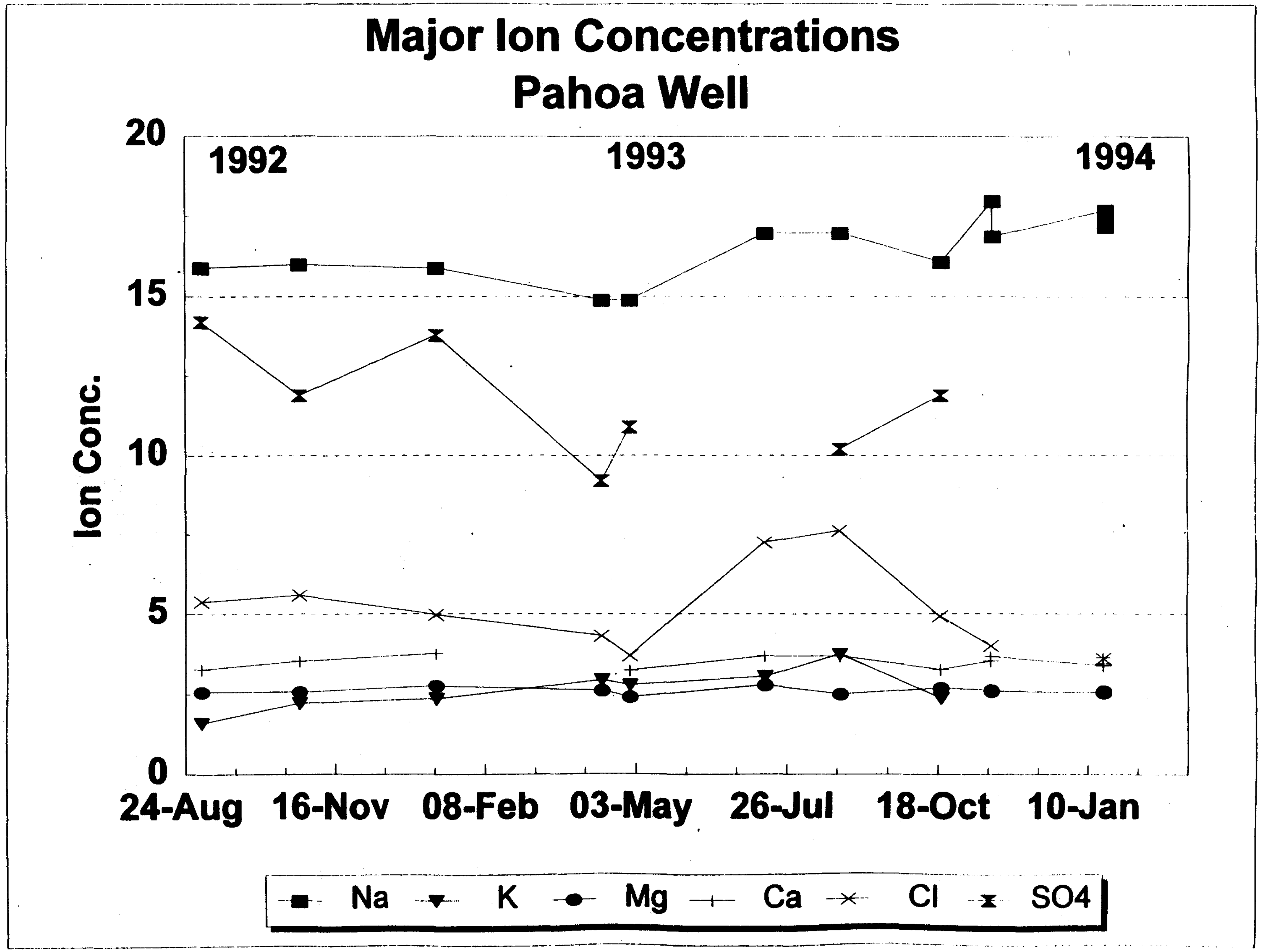

Major Ion Concentrations
Pahoa Well
Ion Conc.
20
15
10
5
0
1992
1993
1994
24-Aug
16-Nov
08-Feb
03-May
26-Jul
18-Oct
10-Jan
Na
K
Mg
Ca
Cl
SO4

Figure 27

Kapoho Airstrip Well

The KAW shows ion concentrations that are up to twenty times those found at the Pahoa Well. Figure 28 presents the time series data for samples taken from the well over the course of this investigation. The arrows in the figure represent the periods during which monitoring instrumentation was installed in the well: during the first interval, only temperature, conductivity, and water level were monitored whereas, during the latter period, a downhole pump was installed with the instrument package allowing us to collect samples without disturbing the instrumental monitors.

The major ion data show substantially more variability at this well that was found for the Pahoa Well series: the coefficient of variation (CV) of the major ion concentrations range up to about 18% with only sulfate, bicarbonate, and silica having CV of less than 10% of their respective means. The higher relative standard deviations may, in part, be attributed to the installation of the downhole pump in the well. The earlier suite of samples in this time series were taken with a bailer sampler collecting water from the surface of the basal groundwater whereas the pumped samples were taken with the pump intake at a depth of approximately 2 m in the well. An evaluation of the relative enrichment factors of the ions (Figure 29) shows that the deeper, higher salinity waters also have a significantly lower enrichment of potassium and sulfate than do the surface waters. This offers further substantiation that the surface waters have a higher geothermal component than does the groundwater deeper in the basal lens. We can further conclude that the stratification of the groundwater here, that was also identified from the tidal response observed in the continuous monitoring data, leads to significant variability in the analytical results obtained for this well.

In addition to the variation in major ion concentrations associated with thermal stratification of the water in this well, there is also a seasonal signal in the groundwater compositions. During the period when the downhole pump was installed in the well, there is a decrease in the concentrations of sodium and chloride from their peaks values in June and July to values of about 30% lower in September and October reflecting dilution of the more saline groundwaters by increased rainfall recharge during the later part of 1993.

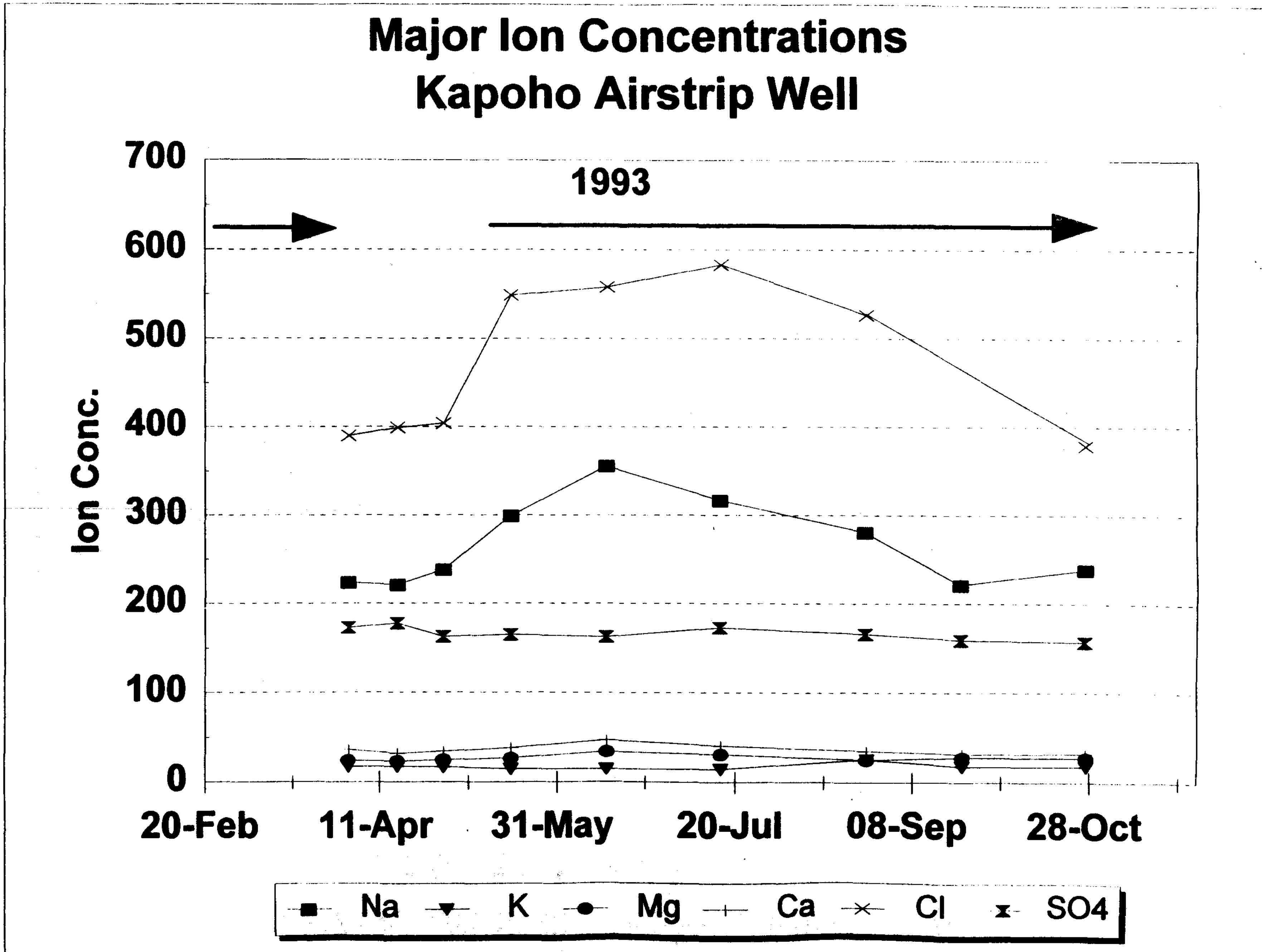

Major Ion Concentrations
Kapoho Airstrip Well
1993
Ion Conc.
700
600
500
400
300
200
100
0
20-Feb
11-Apr
31-May
20-Jul
08-Sep
28-Oct
Na
K
Mg
Ca
Cl
SO4

Figure 28

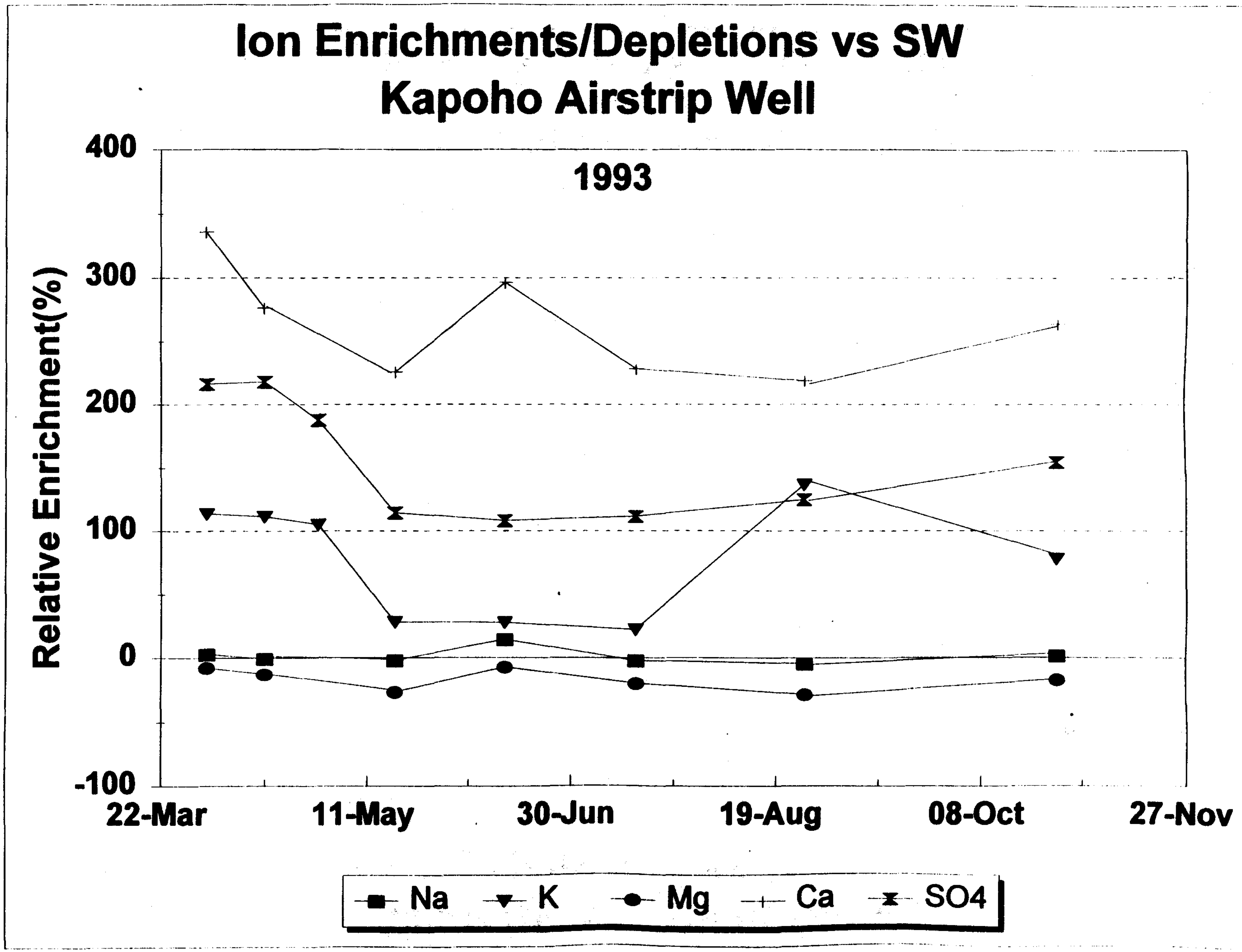

Ion Enrichments/Depletions vs SW
Kapoho Airstrip Well
1993
Relative Enrichment(%)
400
300
200
100
0
-100
22-Mar
11-May
30-Jun
19-Aug
08-Oct
27-Nov
Na
K
Mg
Ca
SO4

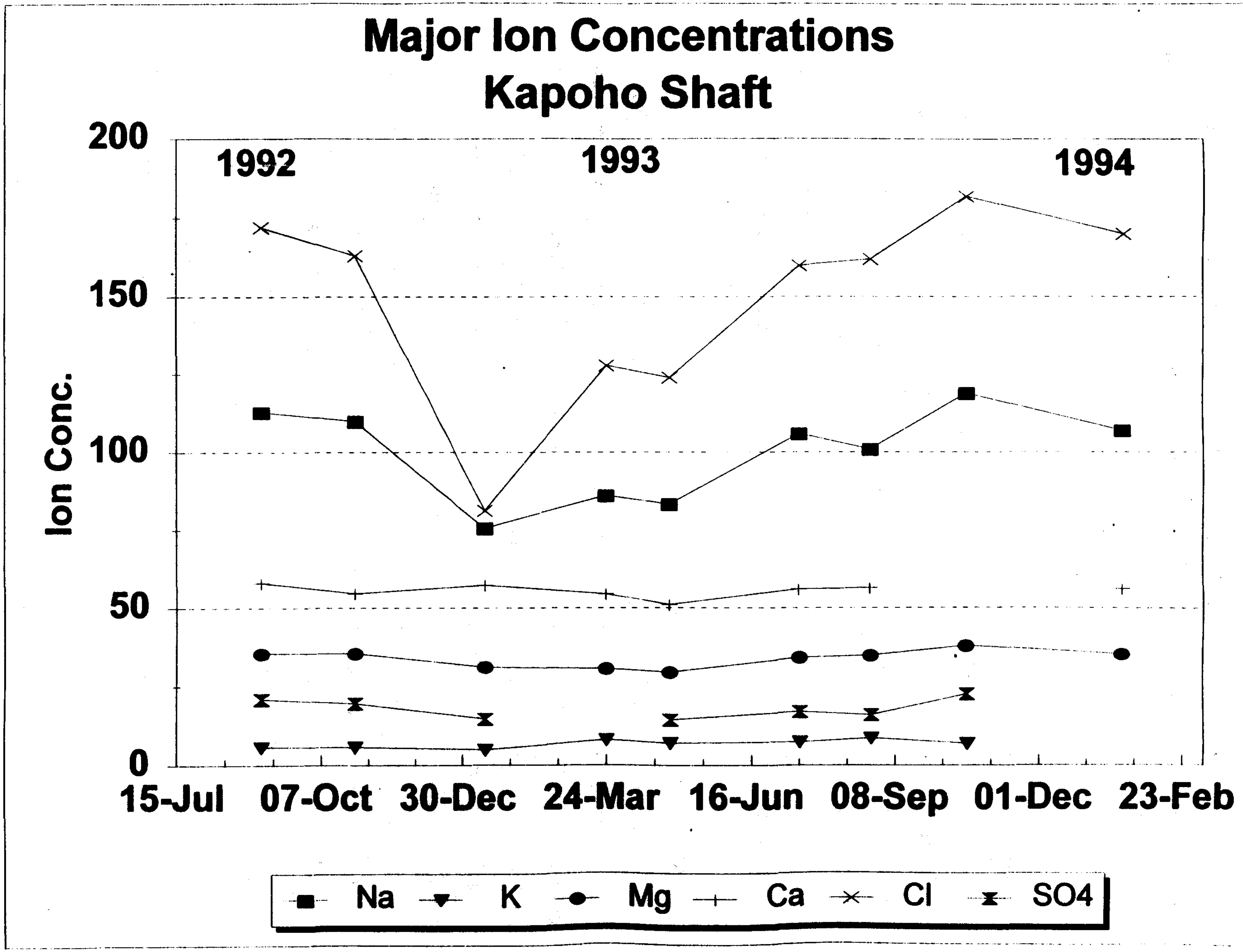
Figure 29

The time series data thus indicates that thermal stratification in the wellbore and seasonal variations in rainfall recharge induce substantial variability in the major ion concentrations in the basal groundwaters at the KAW.

Kapoho Shaft Well

The Kapoho Shaft Well is located about 10 km ENE of the geothermal field currently under development. It is the easternmost shallow well on the rift zone and is located on the ash bed of Kapoho Crater cone. Earlier studies of he well have shown that local water table is sensitive to tidal flux and that the chloride concentrations vary with seasonal rainfall. The average compositions of the water samples collected here strongly indicate that this groundwater system is isolated from that over much of the KERZ: major cations show ion-to-chloride ratios that are markedly different from those of any other well on, or north of, the rift and this is the only well for which bicarbonate is the major anion.

The time series data for KSW further supports this conclusion. The data show significant variability in the chloride and sodium concentrations with time but less change in the magnesium or calcium ions (Figure 30). The calculated coefficient of variation for the ion concentrations shows that, potassium, and sulfate concentrations change markedly over the course of the sampling interval. In contrast, magnesium, calcium, and bicarbonate ions show much smaller coefficients of variation. This response is interpreted to indicate that the groundwater is derived from rainfall recharge, modified by solution reactions in the Kapoho Cone ash bed, mixing with seawater infiltration into the aquifer. The latter component is responsible for the bulk of the chloride, sodium, potassium, and sulfate ion whereas magnesium, calcium, and bicarbonate are derived from solution reactions in the ash bed. Hence, rainfall events are likely to have a strong impact on the groundwater compositions in this water supply but changes in basal groundwater quality outside of this confined area are unlikely to affect the chemistry seen in the Kapoho Shaft Well. Because of its unique characteristics, this water source is not expected to show any effects from the geothermal development activities occurring up-rift.



Major Ion Concentrations
Kapoho Shaft
1992
1993
1994
Ion Conc.
200
150
100
50
0
15-Jul
07-Oct
30-Dec
24-Mar
16-Jun
08-Sep
01-Dec
23-Feb
Na
K
Mg
Ca
Cl
SO4

Figure 30

MW-1

The MW-1 well is located north of the geothermal production and reinjection field on the PGV lease. The well was drilled in 1990 to a depth of 220 m and supplies on-site needs of the power plant. **It is pumped on a routine basis at withdrawal rates of — gpm.** The water produced by the well has a measured temperature of about 44°C and clearly indicates that a geothermal component is present in the basal water here. The average values of the dissolved ion concentrations of the MW-1 water presented above show that the composition of the basal water here is much different from that at most other wells in Puna; sulfate is the major anion with a concentration about ten times that of chloride or bicarbonate and potassium and calcium show substantial enrichments over a diluted seawater composition. Although these characteristics suggest that this water could be derived from a mixture of thermally modified seawater and rainfall recharge, magnesium ion is also enriched which is inconsistent with such a composition. A more probable source for the basal water here is a mixture of freshwater recharge and geothermal steam: the former providing the enrichment of potassium, calcium, and magnesium and the latter providing sulfide which oxidizes to sulfate on mixing with oxygenated groundwater.

Time series sampling from this well began in late 1991 and the data since that time shows relatively modest variation in the ion concentrations with no clear seasonal trend evident in the concentrations (Figure 31). None-the-less, the coefficient of variation of the data (Table 3) shows a higher degree of variability than would be expected for analytical variations alone (5% for most ions). The variability observed may be associated with the effects of differing pumping rates from this well: changing amounts of draw-down and mixing with underlying saline water would be expected to have a substantial impact on the absolute and relative ion concentrations in the dilute groundwater found here.

Monitoring Well 3

The MW-3 well is located within 30 m of MW-1 and was also drilled for the purpose of providing on-site water for power plant and well drilling operations. Over the course of this study, it was pumped only intermittently; at the conclusion of the drilling operations, the well was placed on standby and has not been sampled after November, 1992. The water compositions

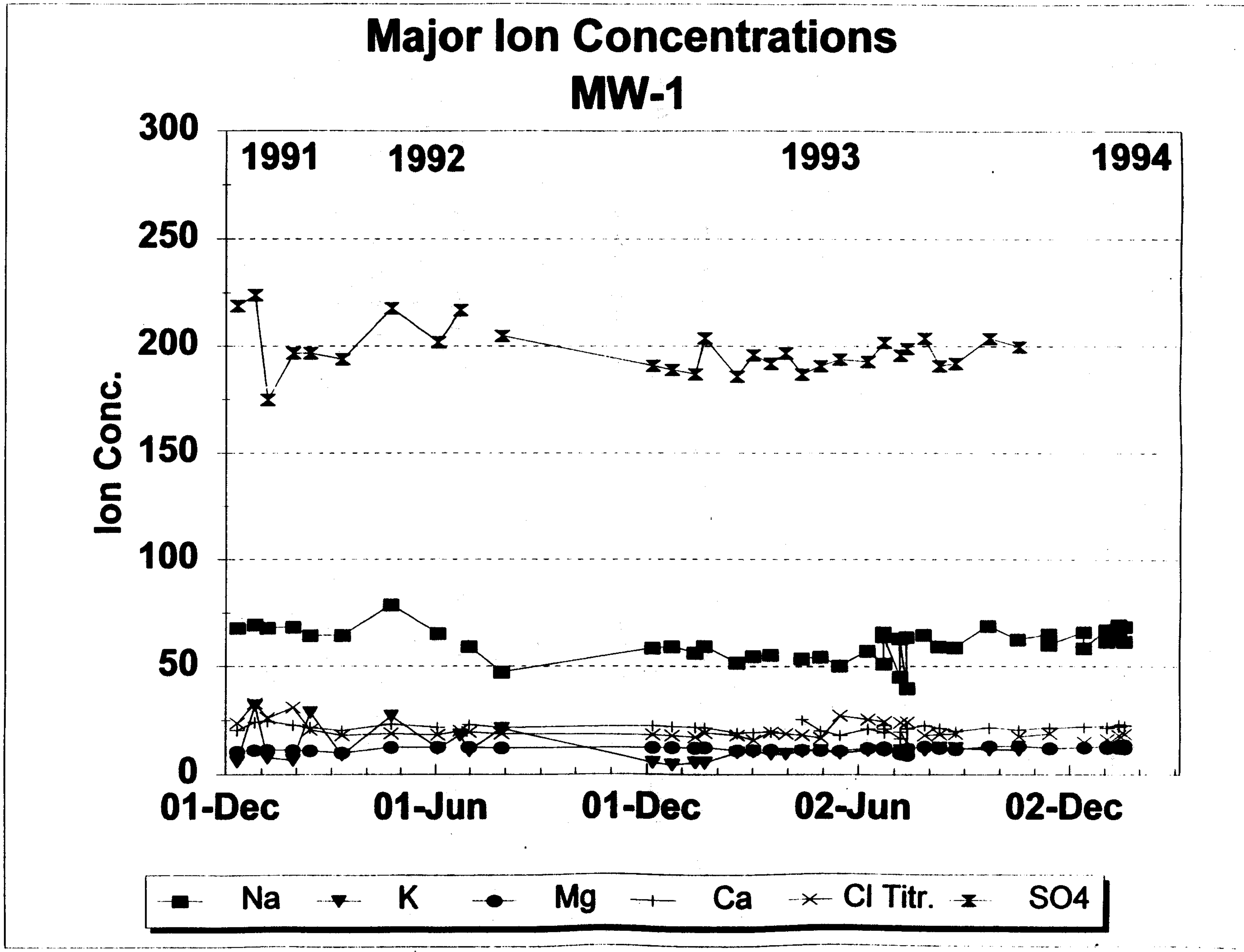

Major Ion Concentrations
MW-1
Ion Conc.
300
250
200
150
100
50
0
1991
1992
1993
1994
01-Dec
01-Jun
01-Dec
02-Jun
02-Dec
Na
K
Mg
Ca
Cl Titr.
SO4

Figure 31

found during the sampling program are very similar to those found in MW-1 with the major significant difference being that the chloride concentration is about 30% higher in MW-3 (Figure 32). This difference is attributed to the greater depth from which MW-3 draws its water: although both wells are drilled to the same depth, perforated casing in MW-3 begins is placed about 20 m deeper than in MW-1. The CV for the ion chemistry show greater variability in sulfate and chloride than are seen for the other ions in MW-3 or for the same ions in MW-1 well. This again may be a reflection of withdrawal of fluids from deeper in the basal water system where mixing may be more likely to occur.

Geothermal Test Well 3

The GTW-3 well is located approximately 1 km ENE of the production and reinjection field currently under development and is currently used as an observation well. The well was drilled in 1962 to a depth of 180 m and was recently cleared of debris and re-fitted with a slotted casing string. The basal groundwater at this site is moderately saline and has a temperature of about 93°C. The ion compositions at this site show clear evidence that the source of the saline water is from thermally altered seawater.

The well was first sampled for this study in November 1991 and has been sampled on about a monthly frequency since that time. Although an attempt was made to install a downhole sample pump at this location, the pump was unable to withstand the groundwater conditions here and failed within a few weeks of installation. Hence, all but one of the samples from this site were taken with a downhole bailer sampler.

The time series data for this site shows relatively stable ion concentrations for most of the duration of the study (Figure 33). Exceptions to this occurred during the first month of sampling when concentrations increased by a factor of about 2.5, and in May 1993, when concentrations increased for a single sample. Both of these excursions from the mean values are considered to be the result of external influences on the well. The initial increase in ion concentrations is believed to be the result of a well clean-out that occurred prior to utilization of this well; it is likely that fresh water pumped into the well during the work-over had not yet dissipated when the first samples were taken. The May 1993 sample was the only one taken with the downhole sample pump and is likely to have sampled from a different point in the water column; hence the

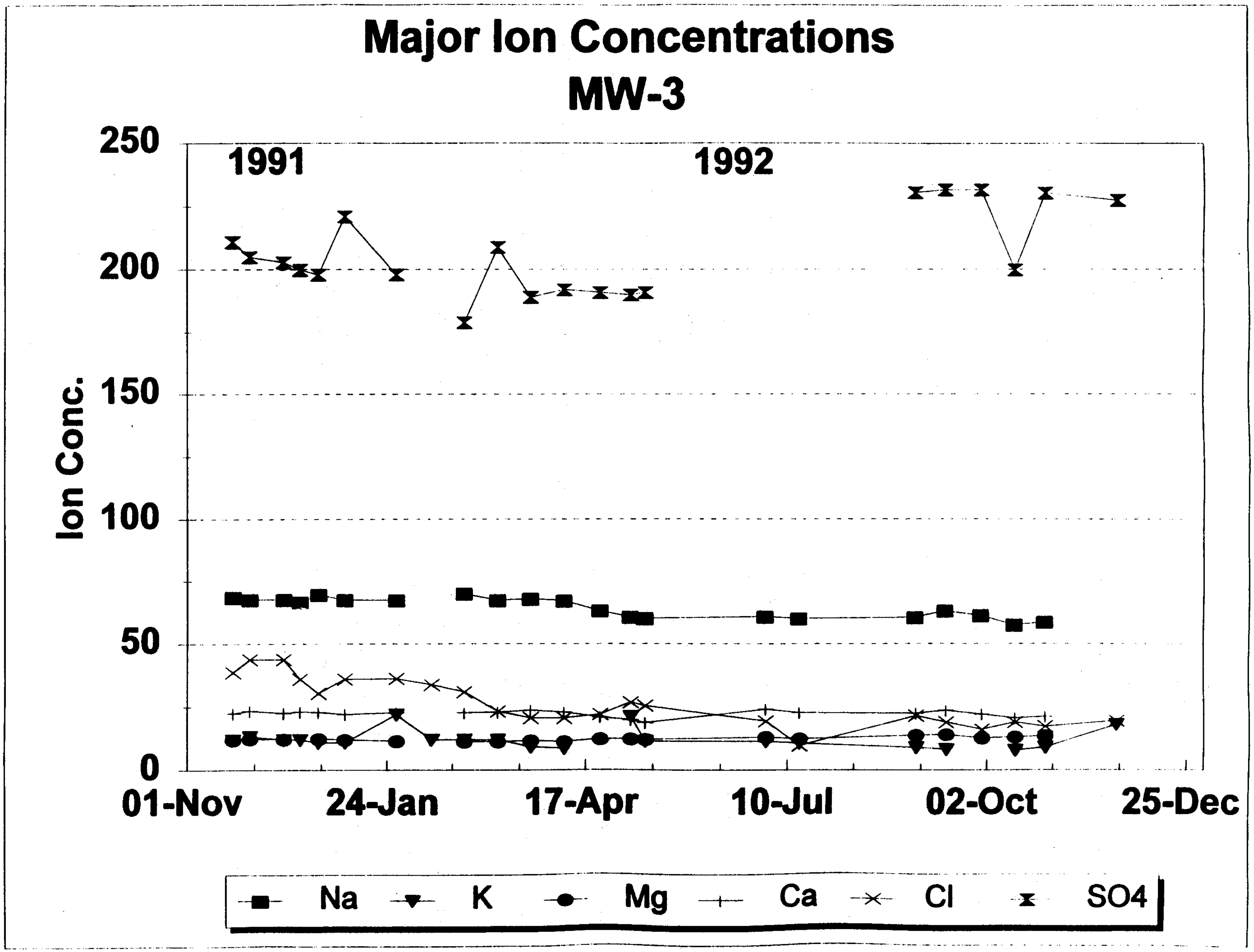

Major Ion Concentrations
MW-3
1991
1992
Ion Conc.
250
200
150
100
50
0
01-Nov
24-Jan
17-Apr
10-Jul
02-Oct
25-Dec
Na
K
Mg
Ca
Cl
SO4

Figure 32

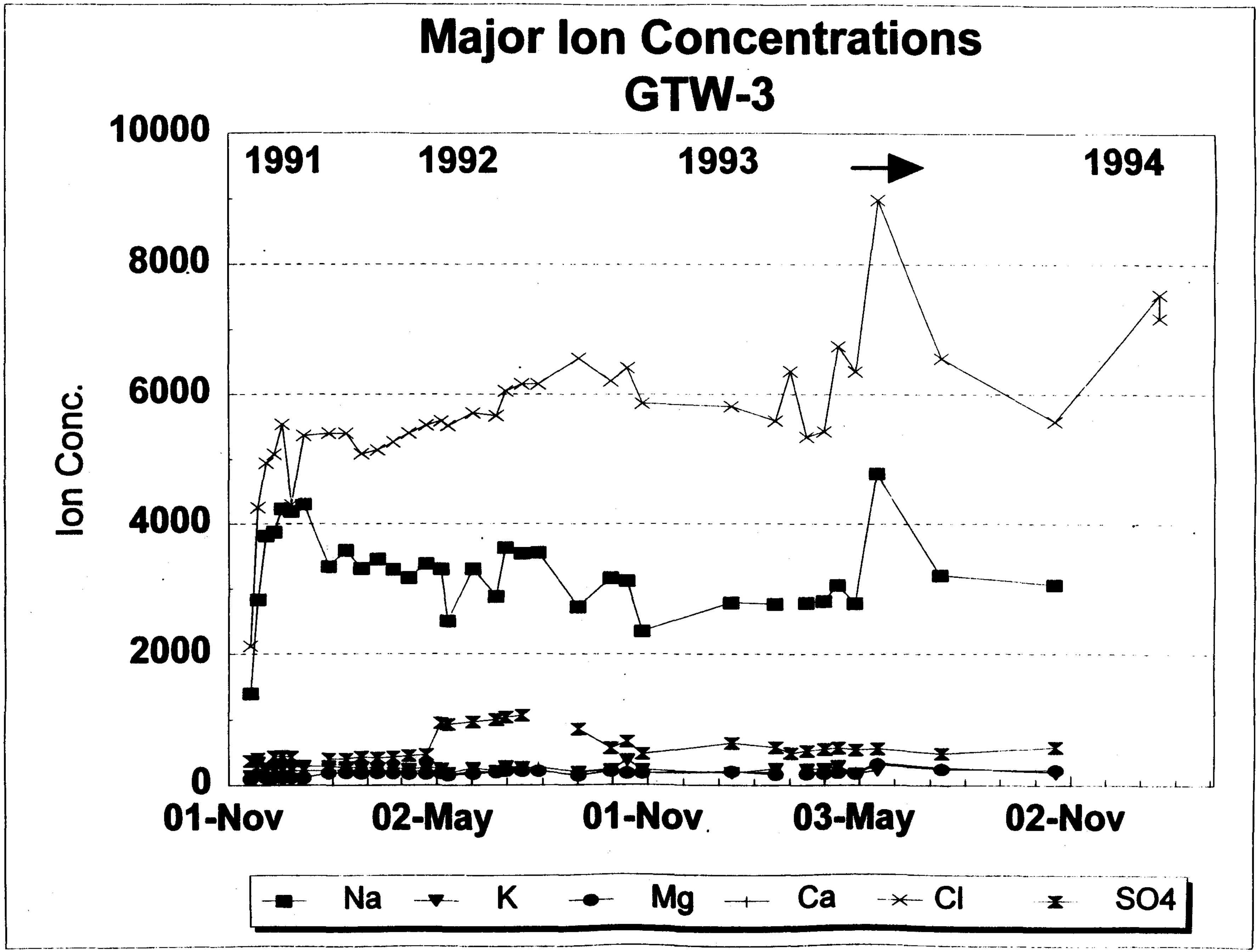

Major Ion Concentrations
GTW-3
10000
8000
6000
4000
2000
0
Ion Conc.
1991
1992
1993
1994
01-Nov
02-May
01-Nov
03-May
02-Nov
Na
K
Mg
Ca
Cl
SO4

Figure 33

sample is not directly comparable to the bailer samples taken during the remainder of the monitoring interval.

Beyond the externally imposed variations in ion concentrations, there appears to be a modest variation in the composition of the basal water as a result of seasonal changes as well as sampling variability. The former effect is seen in the decline in sodium concentrations of about 20% during late 1992 and early 1993 which is contemporaneous with an increase in rainfall recharge and reflects more freshwater entering the system at this time. Some of the sample-to-sample variability is, however, attributed to the effects of taking a bailer sample of a stratified basal water system: mixing within the wellbore, as well as differences in depth of sample entry into the bailer, are expected to have a significant impact on the sample compositions in a highly stratified well such as GTW-3 is known to be. The combination of the natural variability and sampling uncertainty produces a CV in the ion concentrations ranging between 11% and about 20% for GTW-3. The range of variation in the ion concentrations is somewhat smaller than would be expected for a saline well in a high rainfall area (c.f. KAW, KSW, or MKW) and is interpreted to suggest that the system from which GTW-3 draws may be partially isolated from the larger basal water system through which large volumes of fresh rainfall recharge moves.

Monitoring Well 2

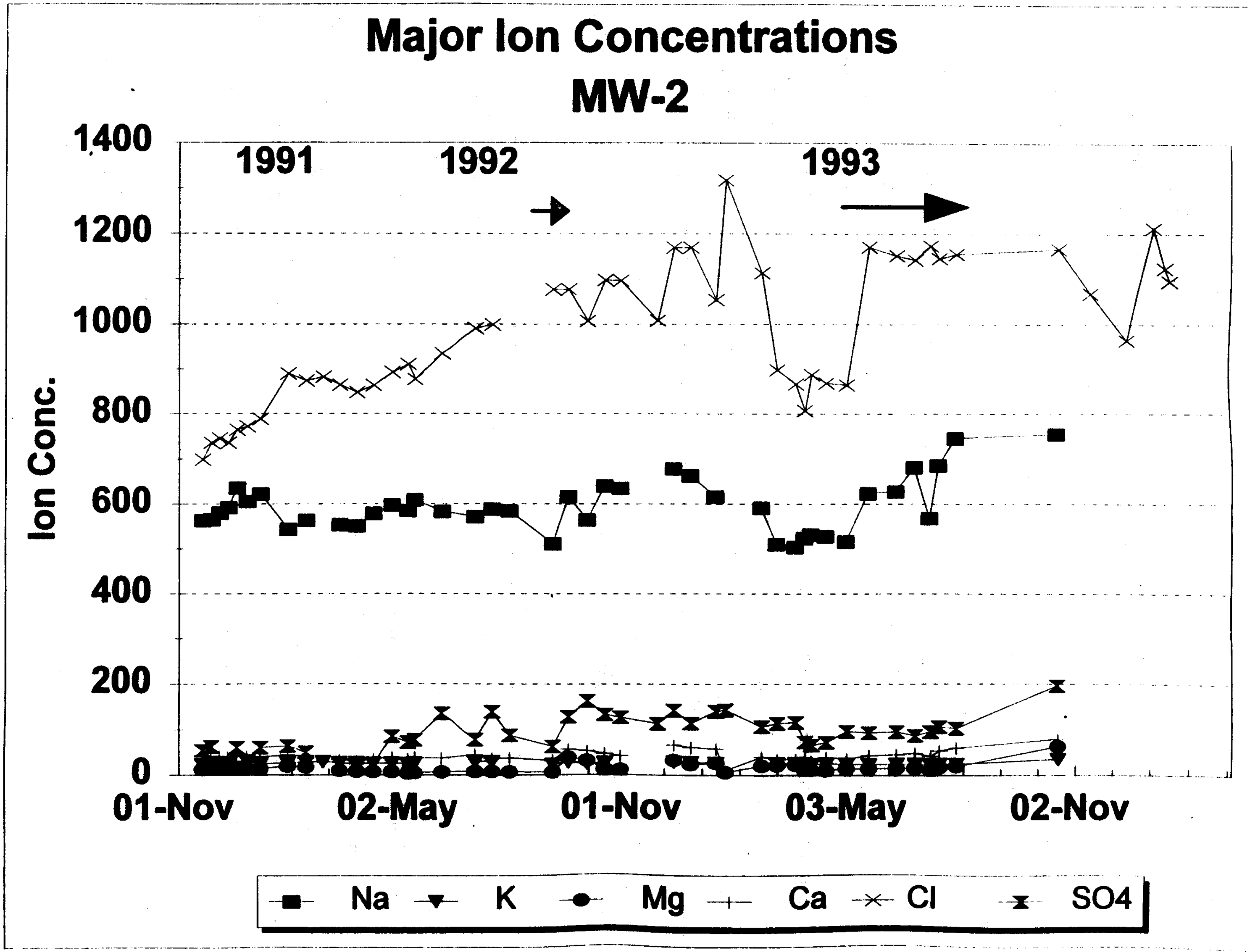
The MW-2 well was drilled for the purpose of providing data on the basal groundwater table in close proximity to the production and reinjection field that is under development. As noted earlier, this well has a temperature of about 65°C making it the second hottest well in the rift zone. The average salinity of the water at this location is about 20% of that of the GTW-3 well but is still more than 20 times that of MW-1 and MW-3 fluids. It is noteworthy that, eventhough the salinity and temperature of MW-2 are substantially higher than those of MW-1 and MW-3, the sulfate compositions of the latter are about twice that found at MW-2. As noted earlier, the pattern of enrichments and depletions of the major ions in the fluids here are interpreted to show a strong contribution of natural geothermal discharge to the basal groundwater system in this.

Monitoring of the detailed chemistry at this site began in November 1991 and has continued up to the present time. As described earlier, this site was instrumented with continuous monitoring equipment in August, 1992 and again in March, 1993. In the first instance, the monitoring equipment failed in less than a month whereas, in the latter, the pump failed after about four months of operation and had to be removed to allow routine sampling to continue. The time series data show a progressive increase in chloride during the early sampling period with two episodes of decreased chloride concentrations in late 1992 and late 1993 that are contemporaneous with seasonal increases in rainfall (Figure 34 and 35). The former dilution event is evident in the sodium data as well. The 20% to 30% change in dissolved ion concentrations that coincide with the increased rainfall are interpreted to be the result of increased recharge diluting the mixed basal groundwaters in this area. It should be noted here again that our continuous monitoring data indicated, and it was later confirmed, that the perforations in this well are about 15' below the top of the water table. Hence, the magnitude of the observed changes in ion concentration seen in this well are probably smaller than those that occur in response to rainfall events at the top of the basal lens. The CV for the data at this site range from about 10% for sodium ion to a high of more than 50% for silica and magnesium ion concentrations. The latter coefficients are exceptionally high but may be the result of a combination of the effects of stagnation of the water column in the wellbore and analytical interferences associated with the fluid compositions found at this location.

Allison Well

The Allison Well was drilled in 1962 for the purpose of irrigation but has not been used for this purpose for at least ten years. Our sampling program began in September, 1993 immediately after removal of a defunct downhole pump. The initial sets of samples were taken with a bailer sampler but in November a downhole sampling pump was installed in the well and all subsequent samples have been taken using that pump.

The data that are available indicate that the salinities here are lower than those at MW-2 but higher than the Pahoa wells. Groundwater temperatures average about 39°C and the ion ratios show that the saline fraction present in the basal groundwater at this site is clearly of geothermal origin. Although the time series data currently available for this well are limited in number, there are apparent changes in ion concentrations with time (Figure 36). Although the first sample shows substantially higher ion concentrations than those found in later samples, we believe that the first data set was affected by the disturbance to the water column caused by removal of the



Major Ion Concentrations
MW-2
1400
1200
1000
800
600
400
200
0
Ion Conc.
1991
1992
1993
01-Nov
02-May
01-Nov
03-May
02-Nov
Na
K
Mg
Ca
Cl
SO4

Figure 34

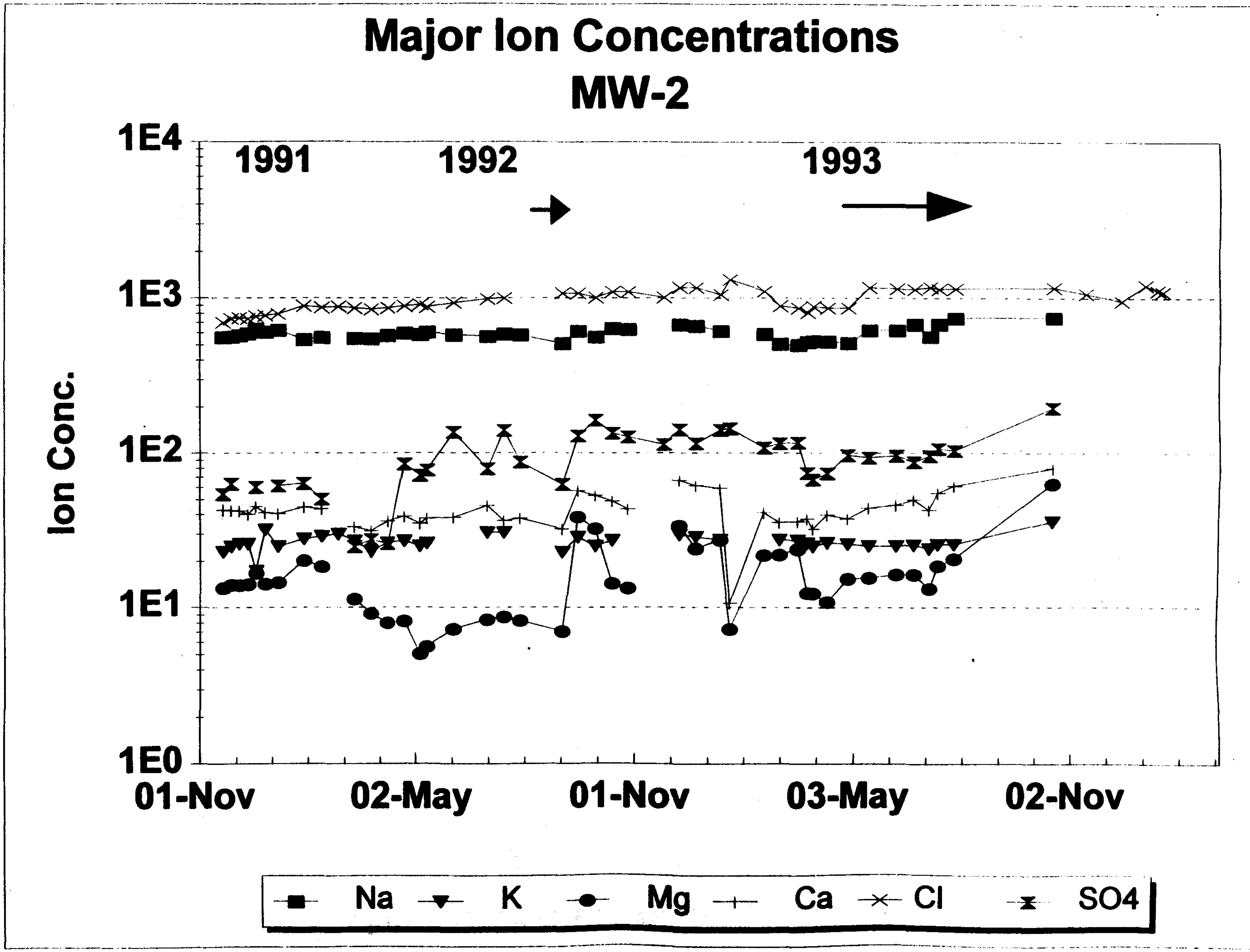
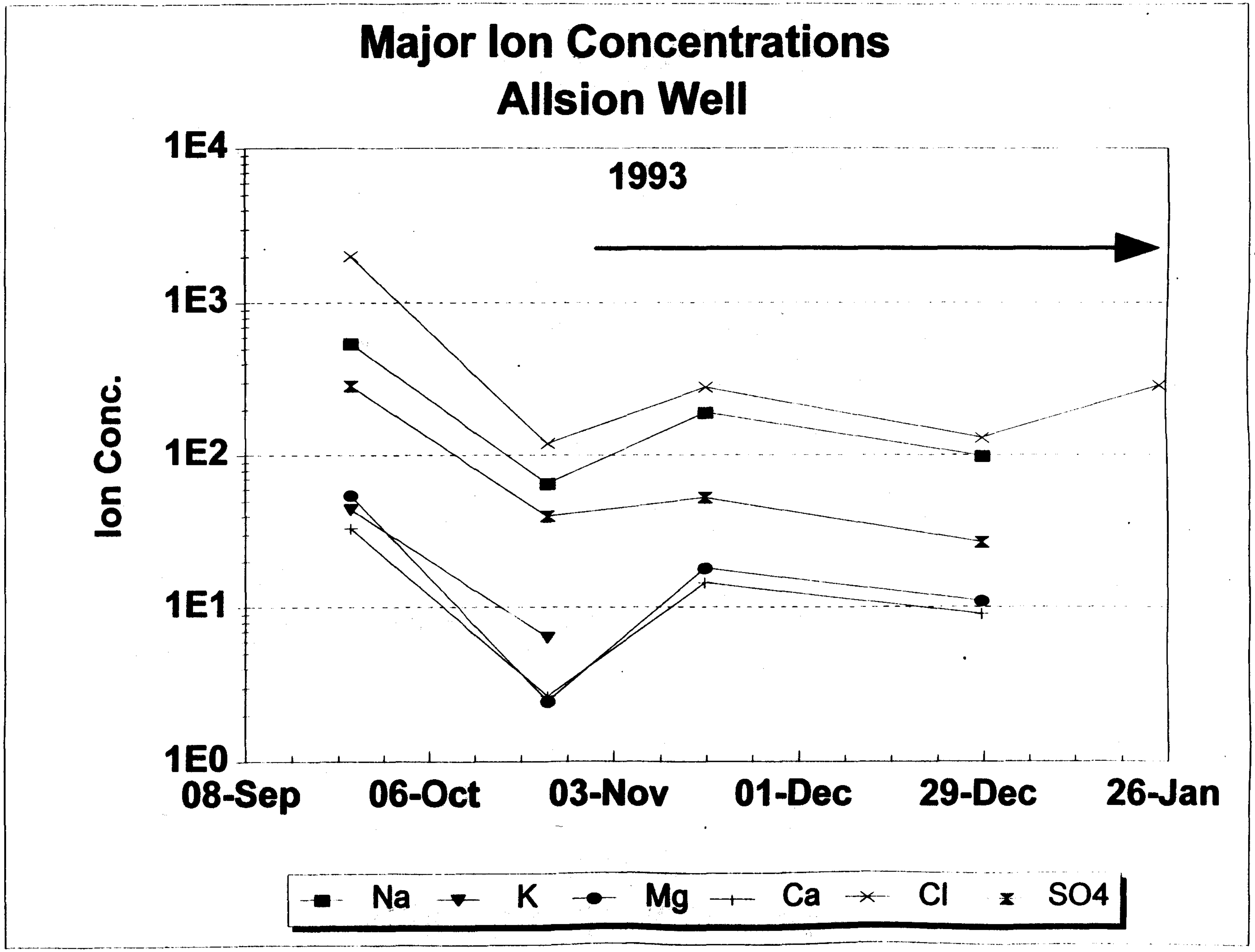

Major Ion Concentrations
MW-2
1E4
1E3
1E2
1E1
1E0
Ion Conc.
1991
1992
1993
01-Nov
02-May
01-Nov
03-May
02-Nov
Na
K
Mg
Ca
Cl
SO4

Figure 35



Major Ion Concentrations
Allsion Well
1993
1E4
1E3
1E2
1E1
1E0
Ion Conc.
08-Sep
06-Oct
03-Nov
01-Dec
29-Dec
26-Jan
Na
K
Mg
Ca
Cl
SO4

Figure 36

downhole pump. Subsequent samples show variations that are believed to be the result of changes in rainfall recharge that occurred during the last quarter of 1993. However, given the short interval over which we have data, it is not possible to make a realistic estimate of the natural variation in the groundwater quality that should be anticipated at this location. Continuing sampling and analysis of the groundwater compositions at this location over the next year should provide the data set required to make this estimate.

Malama Ki Well

The Malama Ki well is located on the south flank of the KERZ and is considered to lie outside the probable influence of the production and reinjection activities at the PGV field. None-the-less, the elevated temperature and relative ion ratios of the groundwater here clearly indicate a substantial contribution of geothermal fluids to the basal water table in this area and thus, this groundwater system can serve as a reference location to evaluate changes in groundwater/geothermal mixing in response to naturally occurring changes in recharge. Sampling began at this station in January, 1992 and has continued to the present (Figures 37 and 38). Groundwater monitoring arrays were installed in the well for two periods (denoted by the arrows in the figures) during our work at this site. During the first interval the instrument array was installed alone but during the second, a downhole sampling pump was also installed. Failure of the instrument array terminated the first monitoring interval and the second was shut down by the loss of the sample pump.

The time series data show that the ion concentrations in the basal water system vary by a factor of two between the maximum and minimum concentrations over the monitoring interval. The primary cause of the variation is attributed to changes in rainfall recharge that dilutes the saline geothermal fluids at the surface of the basal lens: the decreases in dissolved solids concentrations coincide with seasonal changes in rainfall on the LERZ. An additional source of variation is sampling uncertainty associated with collection of bailer samples from a stratified well. The combination of seasonal changes in water quality as well as the sampling variability result in a coefficient of variation for the ion concentrations that range from about 20% to about 37%. These coefficients are generally higher than those found for most of the other wells and is an indication of how sensitive to seasonal recharge the basal lens in this area is.

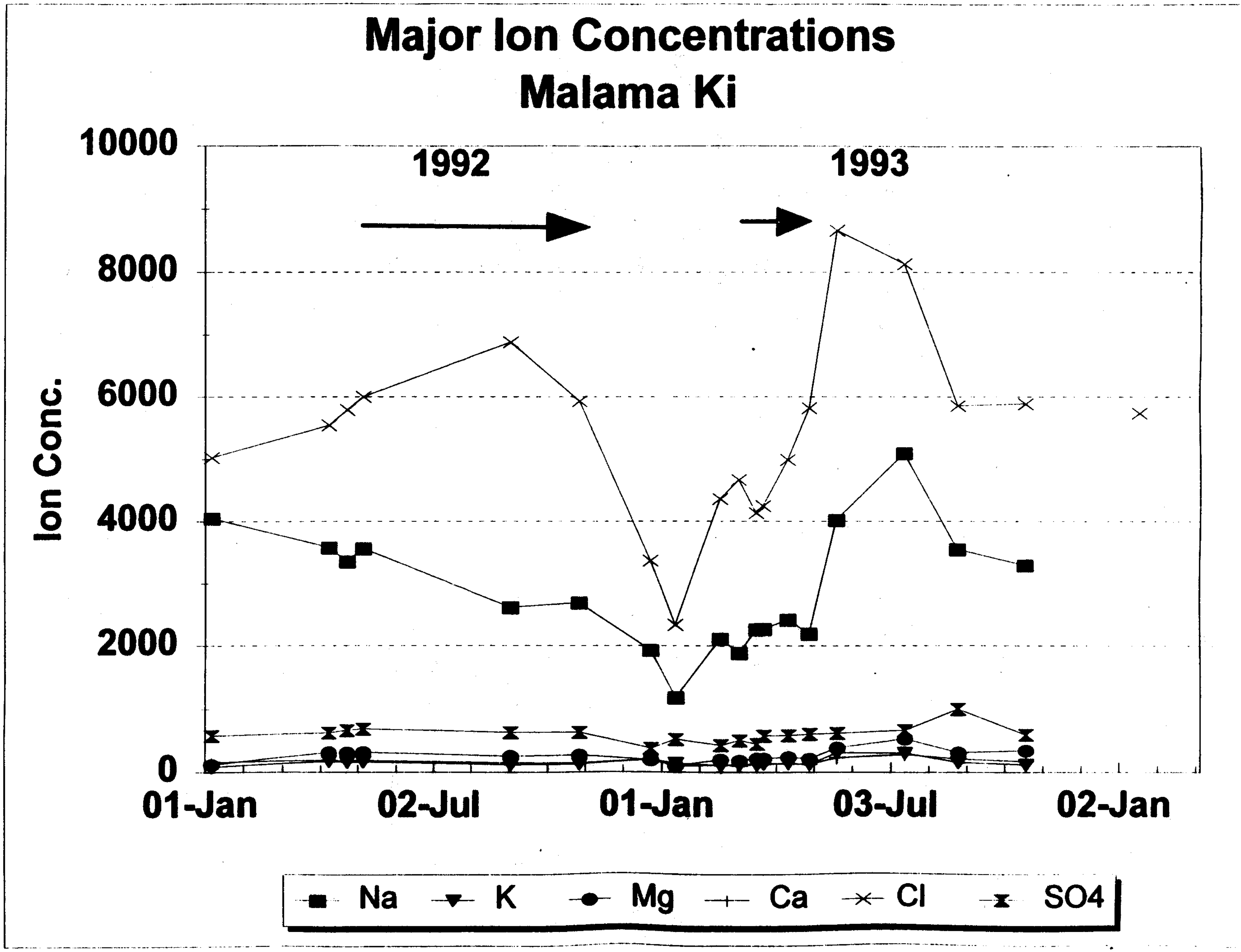

Major Ion Concentrations
Malama Ki
10000
8000
6000
4000
2000
0
Ion Conc.
1992
1993
01-Jan
02-Jul
01-Jan
03-Jul
02-Jan
Na
K
Mg
Ca
Cl
SO4

Figure 37

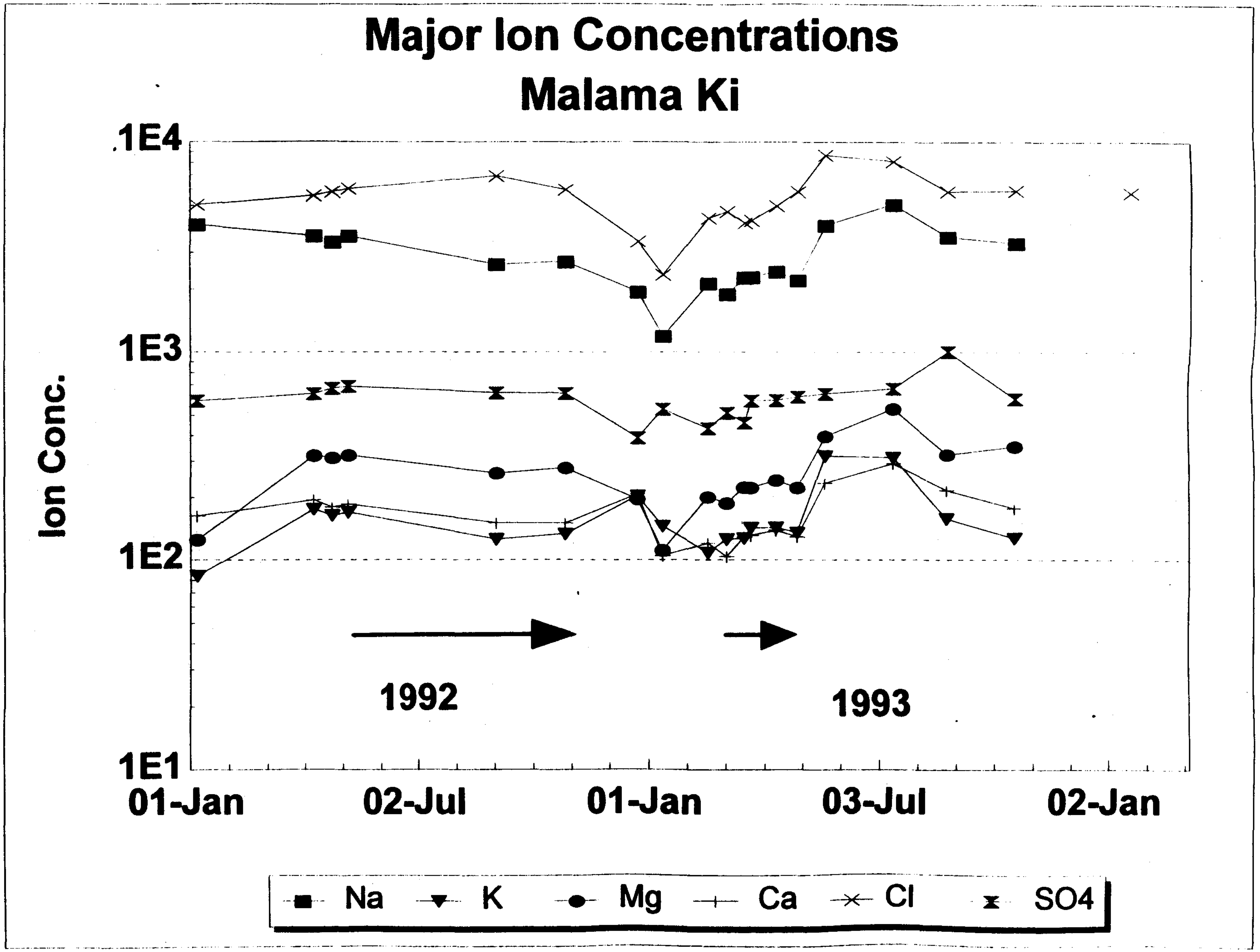

Major Ion Concentrations
Malama Ki
Ion Conc.
1E4
1E3
1E2
1E1
01-Jan
02-Jul
01-Jan
03-Jul
02-Jan
1992
1993
Na
K
Mg
Ca
Cl
SO4

Figure 38

Summary of Geochemistry Monitoring Results

The geochemistry monitoring results have identified and delineated a number of important characteristics of the groundwater system on the eastern flank of Kilauea. The most important of these for the current program are the following:

1) There is no single system (or composition) that characterizes the basal groundwater in lower Puna. There appears to be an evolution of compositions that range from nearly pure rainfall recharge, with varying admixtures of seawater, to recharge mixed with steam-heated waters and with seawater derived brine discharged from the thermal system in the KERZ.

2) The groundwater aquifers north and south of the rift show high tidal efficiencies (indicating good hydraulic communication with the ocean) whereas MW-2, located within the rift shows a much lower tidal efficiency.

3) The temporal variations in groundwater show that all the individual systems are sensitive to rainfall recharge effects. The geochemical and hydrologic data suggest that those wells located within the rift may be more sensitive to rainfall recharge than those located outside the rift zone.

4) Varying compositions of the groundwater in the rift indicate that both brine dominated and steam dominated systems discharge into the basal groundwater. By extension, we can conclude that there are other steam dominated systems such as that discovered by KS-8 well in addition to that already under production.

The implications of these findings for compliance monitoring of groundwater compositions will be dealt with after the results of the geothermal fluid monitoring program are presented.

IV Geothermal fluid monitoring

Monitoring of the chemical composition of the production fluids from the geothermal field currently under development is being done both for environmental compliance as well as for the purpose of reservoir management. Concerns have been expressed that reinjection fluids from the geothermal power plant could enter the shallow groundwater system and cause contamination; in order to identify changes in groundwater chemistry as being the result of geothermal fluid reinjection, it is clearly necessary to characterize the reinjected fluids. The basis for the application of fluid chemical data to reservoir management is based on the fact that changes in production fluids frequently occur prior to major changes in reservoir temperatures and production rates.

Prior Work

Historical precedent for contamination of shallow groundwaters by geothermal reinjection fluids is quite limited since, in the past, very few production facilities in high temperature geothermal fields have employed reinjection and fewer still have monitored the shallow groundwater system for the effects of deep reinjection. Monitoring of the basal groundwaters was done during the operational life of the HGP-A facility where the geothermal fluids contained moderate concentrations of sodium chloride and silica, and relatively low concentrations of the trace transition elements (lead, arsenic, copper, cadmium). The strategy applied was to use the major elements as tracers since dilution of the higher risk minor elements would have been essentially undetectable in the local groundwater system.

Monitoring of the geothermal fluids for the purpose of reservoir management has been based on earlier work in many geothermal fields. These earlier studies have shown that changes in reservoir characteristics associated with declining productivity or depletion of the resource, are frequently preceded by significant changes in fluid chemistry. For water dominated systems, changes in the relative concentrations of sodium, potassium, and calcium, or the absolute concentrations of silica, can signal a decrease in reservoir temperature or the influx of cold surface water that may, over a period of time, reduce reservoir temperatures and fluid productivity. Although steam dominated geothermal systems typically signify loss of reservoir productivity by declining pressures, The Geysers geothermal field has also shown increases in acid gas content (e.g. hydrochloric acid) as the reservoir fluid has become depleted.

The response of the geothermal reservoir on the KERZ to fluid withdrawal is expected to have some similarities to that of other fields but is also expected to show some unique characteristics as well. The HGP-A fluid chemistry showed increases in salinity during its production life as well as changing ratios of sodium, potassium, and calcium. Although the latter suggested that cooler fluids were entering the reservoir feeding HGP-A, the silica concentrations showed little indication of declining temperatures. Because silica equilibrates more rapidly with reservoir temperatures than do the other ions, we have interpreted these changes to suggest that the cooler fluids had not yet affected the reservoir rock temperatures and, hence, that a decline in productivity from that well was not imminent. The brine phase from the HGP-A well also showed a slight decline in pH during its production cycle. This change is believed to be the result of entry of seawater that had not yet had an opportunity to come to equilibrium with the reservoir rocks. Although the fluid pH remained relatively benign during the life of the well, entry of seawater could, under some circumstances, significantly reduce fluid pH.

Monitoring Program

On the basis of this past experience, the species monitored for the purposes of environmental compliance have been as follows: major ion concentrations have been monitored on a routine basis to track the quantities of salt in the saline water disposed of with periodic checks of the trace elements to confirm that their concentrations have not increased to a level that would pose a significant environmental risk. Because the Puna Geothermal Venture project employs complete reinjection of all produced geothermal fluids, we have also monitored the concentrations of the soluble gases, hydrogen sulfide and carbon dioxide, as tracers as well. The constituents monitored for reservoir management include all the constituent analyzed for environmental compliance as well as: dissolved silica and the fluid pH.

Our earlier experience had also shown that changes in fluid compositions frequently occur at a rapid rate during the initial weeks of operation of a well but, with time, a semblance of equilibrium is approached where fluid compositions typically change more gradually. Hence, our sampling protocol was to collect samples at frequent intervals during the initial production phase of each well and to progressively decrease the frequency with time.

The specific sampling protocol was to collect separate samples of the steam phase and the liquid phase produced by each well. The preferred sampling location for these phases was down-stream of the production separators since this allowed us to obtain nearly complete separation of the two-phase mix produced by each well. Sampling at this location also allowed us to obtain data on the mass flow rate of each phase that permitted calculation of total production rates of each constituent of interest. In some cases, however, sampling downstream of the plant separator was not possible either because the separator was not in operation or because the fluids from two wells were mixed at the separator thus preventing us from collecting a valid sample for either well. Under the latter conditions, samples were drawn from a small portable separator attached to a mixed-phase line. In either case, both phases were condensed and chilled under pressure in a stainless steel, water-cooled heat exchanger. The geothermal liquid phase was sampled as: filtered acidified for trace elements, filtered untreated for major elements, pH, and alkalinity, raw untreated for isotopes, and filtered and diluted for silica. The steam phase was sampled using an evacuated glass bomb containing saturated sodium hydroxide to absorb the acid gases.

Geothermal Fluid Monitoring Results

The production characteristics of the Kapoho State wells 9 and 10 are clearly different from that of the HGP-A well and most other wells drilled on the KERZ. Early production results indicated that both wells produced about 85% steam and about 15% liquid at a separation pressure of 220 psig whereas the HGP-A well produced a mixed phase of about 43% steam and 57% liquid. Shut-in pressures for the KS-9 and 10 wells are also quite different from most earlier wells. The latter wells typically showed stable wellhead pressures ranging from a few tens of pounds per square inch to a few hundred pounds but the KS-9 and 10 wells maintain pressures of nearly 2000 psi. The geochemistry of KS-9 and 10 are similarly divergent from that of most prior wells. Early samples of the liquid phase indicated very low concentrations of dissolved solids and, as indicated by Figure 39 and Table IV, chloride and the major ion concentrations in the liquid phase from both KS-9 and KS-10 maintained extraordinarily low values during the first several months of production. As a point of reference, the HGP-A well produced fluids having from 100 to 1000 times the concentrations of chloride, sodium, potassium and calcium that the Kapoho State (KS) wells produced whereas silica in HGP-A was about 4 times that at the KS wells.

The thermodynamic and chemical characteristics of the early production from these wells indicates that the production zone tapped is a steam dominated system: the high wellhead pressures indicate that the wellbore is filled with steam rather than water even during shut-in conditions; the ratio of steam to water in the production fluids is higher than can be produced from a single-phase liquid at the measured reservoir temperatures; and the dissolved ion content in the fluid phase is lower than is found in any groundwater on the LERZ. The presence of a liquid phase in the production fluids is interpreted to be the result of both heat loss during transport to the surface and decompression of single-phase steam from a reservoir pressure of

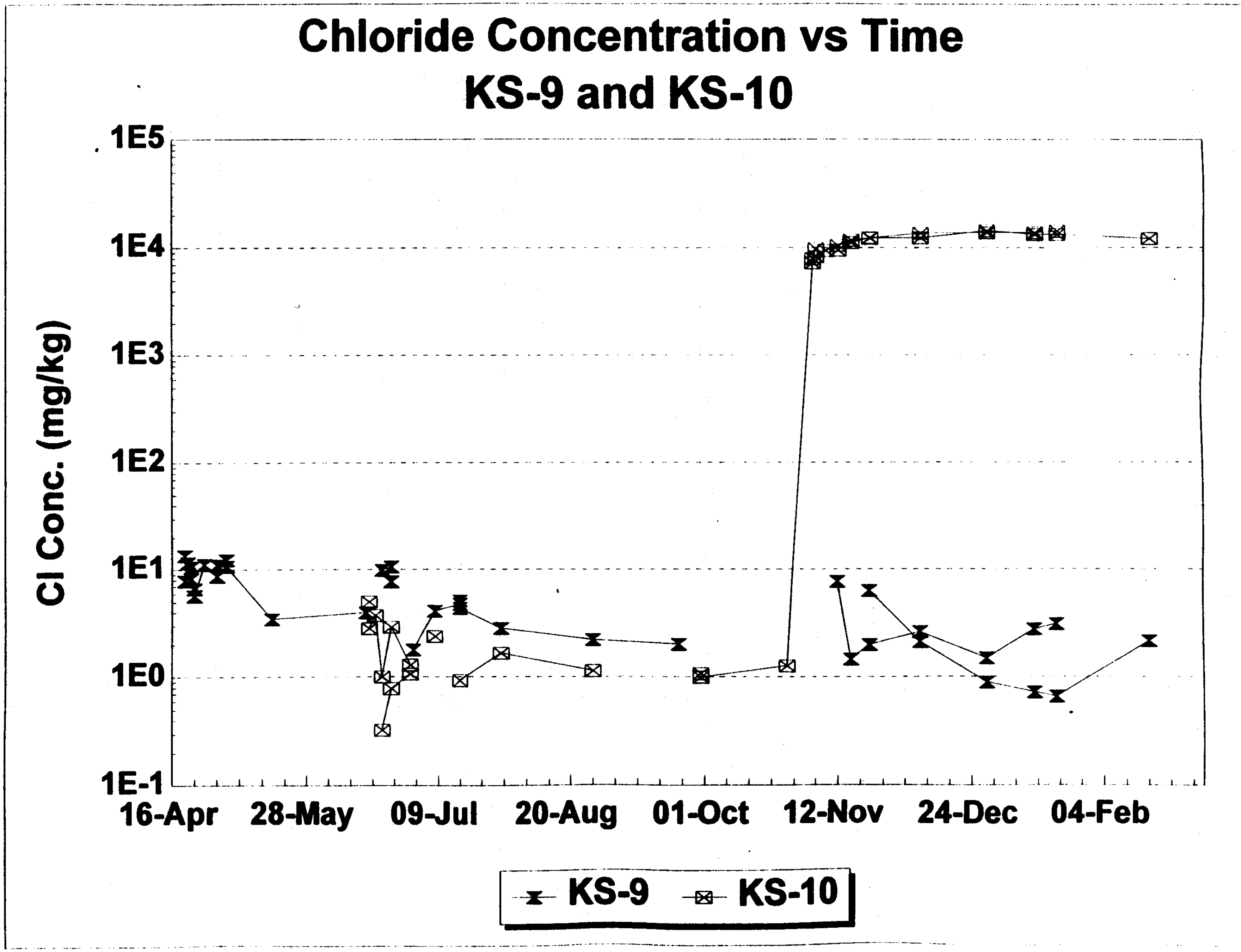

Chloride Concentration vs Time
KS-9 and KS-10
Cl Conc. (mg/kg)
1E5
1E4
1E3
1E2
1E1
1E0
1E-1
16-Apr
28-May
09-Jul
20-Aug
01-Oct
12-Nov
24-Dec
04-Feb
KS-9
KS-10

Figure 39

TABLE IV
Average Geothermal Fluid and Reinjectate Compositions

Average Concentration	Na	K	Mg	Ca	Cl	SO4	HCO3	SiO2	CO2	H2S	Eq. SO4
KS-9	13.3	1.4	0.2	3.4	6	12.3	38.1	206	504	636	NA
KS-10 Pre 11/93	2.4	1.4	0.5	0.4	1.9	5	7.1	196.2	360	560	NA
KS-10 Post 11/93	4904	690	0.1	97.9	11668	9.9	12.2	1087			
Calculated Reinjectate Pre 11/93	1.2	0.2	0	0.3	0.6	1.2	3.4	22	406	539	1,520
Calculated Reinjectate Post 11/93	1178	166	0	23.8	2801	3.4	6.1	127	406	539	1520

about 2200 psi down to 250 psi in the plant separator. The latter process is driven by an increase in the specific enthalpy of steam from 1121 BTU/lb at a pressure and temperature of 2200 psi and 650°F respectively, up to 1200 BTU/lb at 250 psi and 400°F. This effect accounts for about a 7% condensation of liquid from the steam phase.

The condensation process effectively precludes the use of any dissolved species geothermometer. The dissolved solids that are present in the fluid (e.g. silica) are believed to be the result of condensation of gas-phase or aerosol forms of the solids into the condensed water. Furthermore, contact time of the fluids with the reservoir is expected to be both minimal as well as in a state of extreme disequilibrium and, hence, the use of a silica or sodium-potassium-calcium geothermometers will not provide realistic estimates of reservoir temperature.

It is apparent, however, that the concentrations of dissolved solids in the KS-10 well showed a sudden and drastic increase after about 140 days of production. The increase occurred over a span of no more than 8 days: on day 132 chloride levels were slightly above 1 milligram per liter (mg/l) and on day 140 a concentration of more than 7000 mg/l was measured. The change in chemical composition rapidly stabilized at about 13,000 mg/kg Cl after a period of about 45 days and has increased only slightly since then. The increase in dissolved solids concentrations was accompanied by a substantial increase in the relative proportion of liquid from the well: prior to the chloride increase, the water fraction was about 10% and afterward ranged from 60% to 80%.

Possible causes for the increase in chloride concentration are that the steam zone from which KS-10 is producing has become filled with water or that a liquid phase from a higher point in the well has begun entering the wellbore. Application of the sodium-potassium-calcium geothermometer to the recent liquid phase produced by the well indicates that the equilibrium temperature of the fluid is approximately 300°C to 305°C (570°F to 580°F); the silica geothermometer yields temperatures in the same range. These temperatures are somewhat lower than those assumed to be present in the reservoir prior to production (about 650°F) but may reflect some re-equilibration in response to steam withdrawal. These temperatures are consistent with a steam fraction of about 25% at a separation pressure of 250 psi; it is our understanding that the steam fraction of recent production from KS-10 has been in this range. Although it is not possible from the geochemical data alone to conclusively distinguish between the two possible sources of increased brine phase, the currently available data are consistent with an increasing water level in the production formation. None-the-less, even though KS-9 has been in production longer than KS-10, there is no evidence that chloride concentrations have increased significantly in that well which leaves open the possibility that the changing fluid characteristics at KS-10 are of a more local origin.

The levels of environmentally sensitive metals in the KS-9 and KS-10 fluids is generally low. The only minor element concentration that has exceeded 1 mg/kg in the fluids that have been analyzed to date has been boron which has shown concentrations of about 5 mg/kg to 10 mg/kg. The combination of low concentrations as well as the further dilution of these metals with steam condensate prior to reinjection would suggest that the early condensate would pose very little environmental hazard. Analyses are continuing, however, on the later brine phase of KS-10 to determine whether the increase in salinity is accompanied by a significant increase in the concentration of these elements.

The concentrations of non-condensable gases in the geothermal fluids appear to be similar to those found in the HGP-A well with hydrogen sulfide concentrations being nearly equivalent to those in the latter well and carbon dioxide being approximately 30% lower. There appears to be substantial variability in the gas concentrations during the first few months of operation of the well. This may be due to the changing sampling conditions, with variations in operating and sampling pressure, however, some of the variability is also believed to be associated with sampling difficulties. We currently have a backlog of gas samples that will be analyzed as time permits and expect to develop a better assessment of the actual variation in gas concentrations over time.

V. Analysis of Potential Contamination of Basal Groundwaters

One of the objectives of the present study has been to monitor the basal groundwater system in lower Puna for changes that may be associated with production and reinjection of geothermal fluids in the reservoir currently under development. Potential changes in groundwater quality that can be foreseen as possible from each process are as follows:

1) Production of reservoir fluids: if production of geothermal fluids associated with power generation results in a reduction in the reservoir pressure, then the rate of natural discharge of geothermal fluids from the reservoir would be expected to decline;
2) Reinjection: if the fluids being reinjected into the reservoir should cause an overpressure in the reinjection zone, then these fluids may find a pathway back into the shallow surface environment; or
3) If there is a breach in the casing of the reinjection well at a shallow depth, then fluids could leak into the basal groundwater system.

Although an assessment of the likelihood of each of these conditions occurring is beyond the scope of the present study, we can provide an assessment of the types of effects that these events might be expected to have on the groundwater system.

Production of reservoir fluids: The data that have been gathered to date have clearly demonstrated that the basal groundwater within the surface expression (and south of) the LERZ contains geothermal fluids resulting from natural discharges from the underlying hydrothermal system. Hence, a loss of reservoir pressure and a decline in the rate of natural discharge of geothermal fluids from the deep hydrothermal system would be evidenced by a decline in basal water temperatures and a decrease in dissolved solids concentrations. The latter effect would, however, depend on whether the natural discharge was steam dominated or water dominated. The former situation is reflected in the extraordinarily high sulfate concentrations found in MW-1 and MW-3 and, hence, the expected response to a decline in natural output would be a decrease in the concentrations of sulfate ion concentration. Wells that show the effects of a water dominated natural discharge are those which show elevated concentrations of sodium and chloride and have ion ratios that approach those of thermally modified seawater as described above. The wells that fall in this classification would include GTW-3, MW-2, KAW, and the Allison Well. We would anticipate a decline in the concentrations of dissolved solids found in these wells in response to a decline in the natural output from the geothermal reservoir.

The time series data have, however, demonstrated that seasonal changes in rainfall patterns, as well as sampling uncertainties, affect the dissolved solids concentrations found in the Puna monitoring wells. Therefore, a decline in dissolved solids concentrations is not conclusive evidence of a response to geothermal fluid production. In order for a determination to be made of an effect from production, it will be necessary to conduct cross correlation analyses of the groundwater and rainfall data and to identify a statistically valid test that will differentiate between groundwater effects associated with sampling errors and recharge effects and a response to changes in natural reservoir discharges. For the present, a first approximation that can be applied is to compare the changes in ion concentrations with the coefficient of variations calculated for each major ion. A change in the mean values of the data, or a trend in the data that is not associated with a change in rainfall, that is different from the prior mean by more than two standard deviations (or a percentage that is twice the coefficient of variation) can be considered to be significantly different from the mean at a 95% confidence level. Although we do not find any consistent trends or changes in mean ion concentrations over the course of the time series data that meet these criteria, they can be applied in the future to any changes that are observed. It is our intent, however, to evaluate the feasibility of applying other, more robust, statistical tests to the data as part of the normal evaluation process.

Reinjection: An assessment of the potential impact of reinjection fluids that might migrate up into the basal water system will strongly depend on the composition of the reinjection fluids. During the early production from KS-9 and KS-10, both wells produced liquids that contained very low concentrations of dissolved solids. Because steam production from these wells makes up approximately 90% of their total mass flow, and because the steam phase carries virtually no dissolved solids, recombination of the separated liquid phase with the steam condensate produces a reinjection fluid having extremely low concentrations of dissolved ions. An estimate of the dissolved ion concentrations based on the steam and brine production rates and the average dissolved ion concentrations found in the separated liquid phase is presented in Table 4. Comparison of the concentrations of the major dissolved ions in the basal groundwater in lower Puna with those in the reinjectate indicates that entry of the early reinjection fluids into the groundwater system would result in a decline in the major ion concentrations. However, as indicated in the table, the reinjection fluids also contain significant concentrations of carbon dioxide and hydrogen sulfide from the condensed steam phase. The data from MW-1 and MW-3 indicate that, if the reinjection fluids containing these gases were to enter the shallow groundwater, the hydrogen sulfide would probably be oxidized to a sulfate ion and hence, entry of reinjectate would be evidenced by an increase in sulfate ion in the basal water system. An evaluation of the early (pre-November, 1993) time series data does not show any systematic increase in sulfate concentrations in the monitoring wells around the reinjection field that could be attributable to entry of reinjectate into the basal groundwater system.

In November 1993 the production characteristics of KS-10 changed and the well began to produce a higher proportion of liquid having a higher dissolved solids concentration. A calculation of the reinjectate compositions based on the later production characteristics is also presented in Table 4. The data here show that, although sodium and chloride concentrations are substantially higher in the later reinjectate, the ion that exceeds background values in MW-2 by the greatest percentage is still sulfate and, hence, this ion would be the best indicator ion for this well. Using the criteria discussed above, the concentration of sulfate would have to increase by approximately 80 mg/kg at MW-2 before we could say with a high degree of confidence that there was an externally induced change in sulfate compositions. The required increase in sulfate concentrations is equivalent to a contribution of about 5% reinjectate in the MW-2 basal water which would result in a chloride change of about 100 mg/kg, well below the 300 mg/kg change that is required by the test criteria. A similar calculation for the currently available data for Allison well shows that a contribution of about 1.8% of the reinjectate to the basal water would be sufficient to increase the sulfate concentrations to levels that would meet the test criteria.

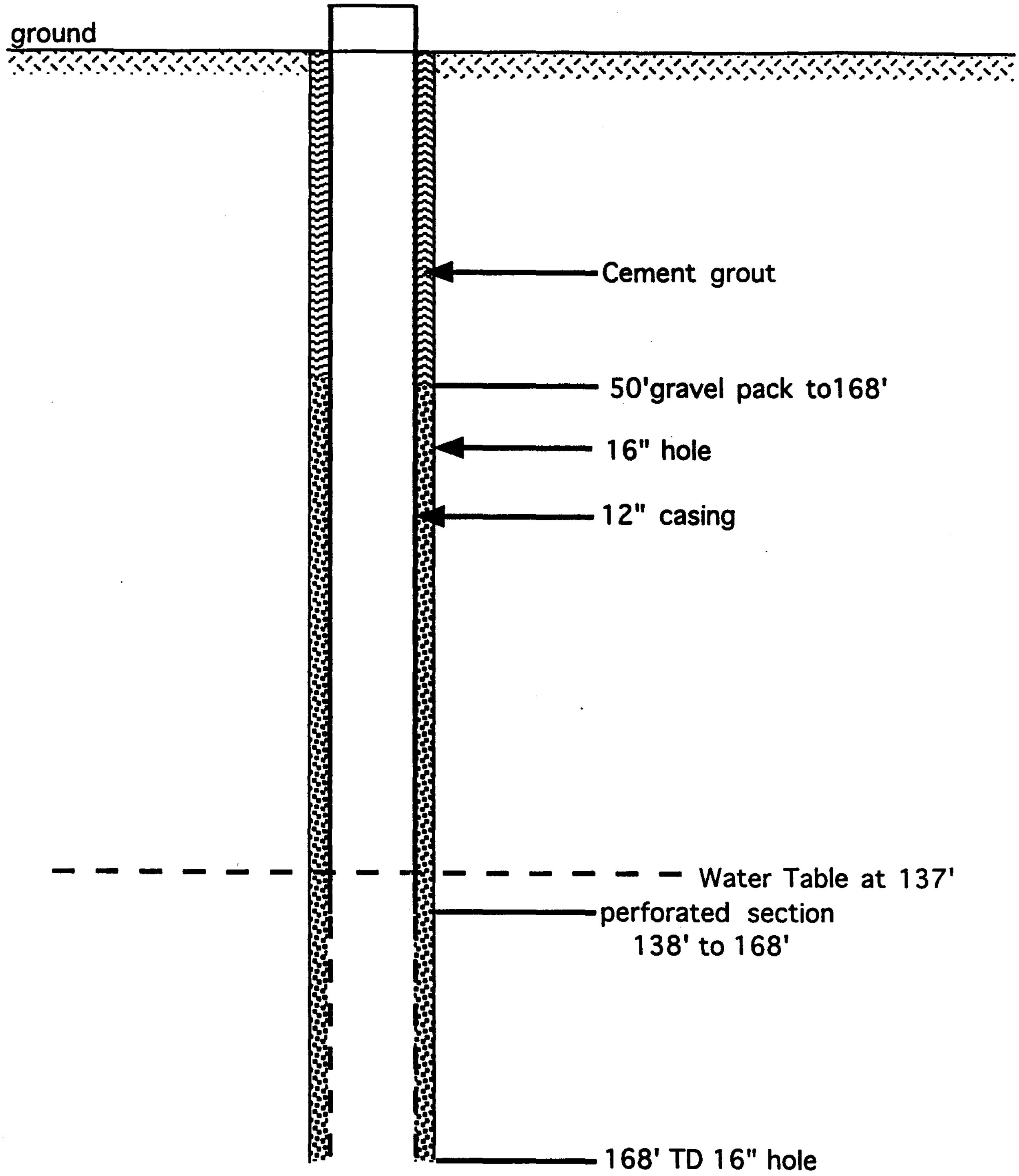
In the case of MW-1 and MW-3, which have high sulfate but low chloride and sodium values, an indication of entry of reinjection fluids would be first visible by changes in the latter ions. A change in the chloride ion concentration by about 17 mg/kg would be required to identify a change in the compositions in the basal water at this location. This is equivalent to a contribution of only 0.6% of reinjectate to the basal water at MW-3.

Although the above estimates of the required changes in ion compositions and equivalent contributions of reinjectate are useful guidelines, we note again that in order to confirm that future changes in ion compositions are the result of reinjectate contamination will require a comparison of all of the changes in ion concentrations for basal water with the composition of the reinjectate to demonstrate that the observed changes were consistent with an addition of reinjectate with the basal water compositions. It should also be understood that, as more groundwater data are gathered, the test criteria will change as the coefficient of variation increases or decreases in response to natural variations in groundwater compositions.

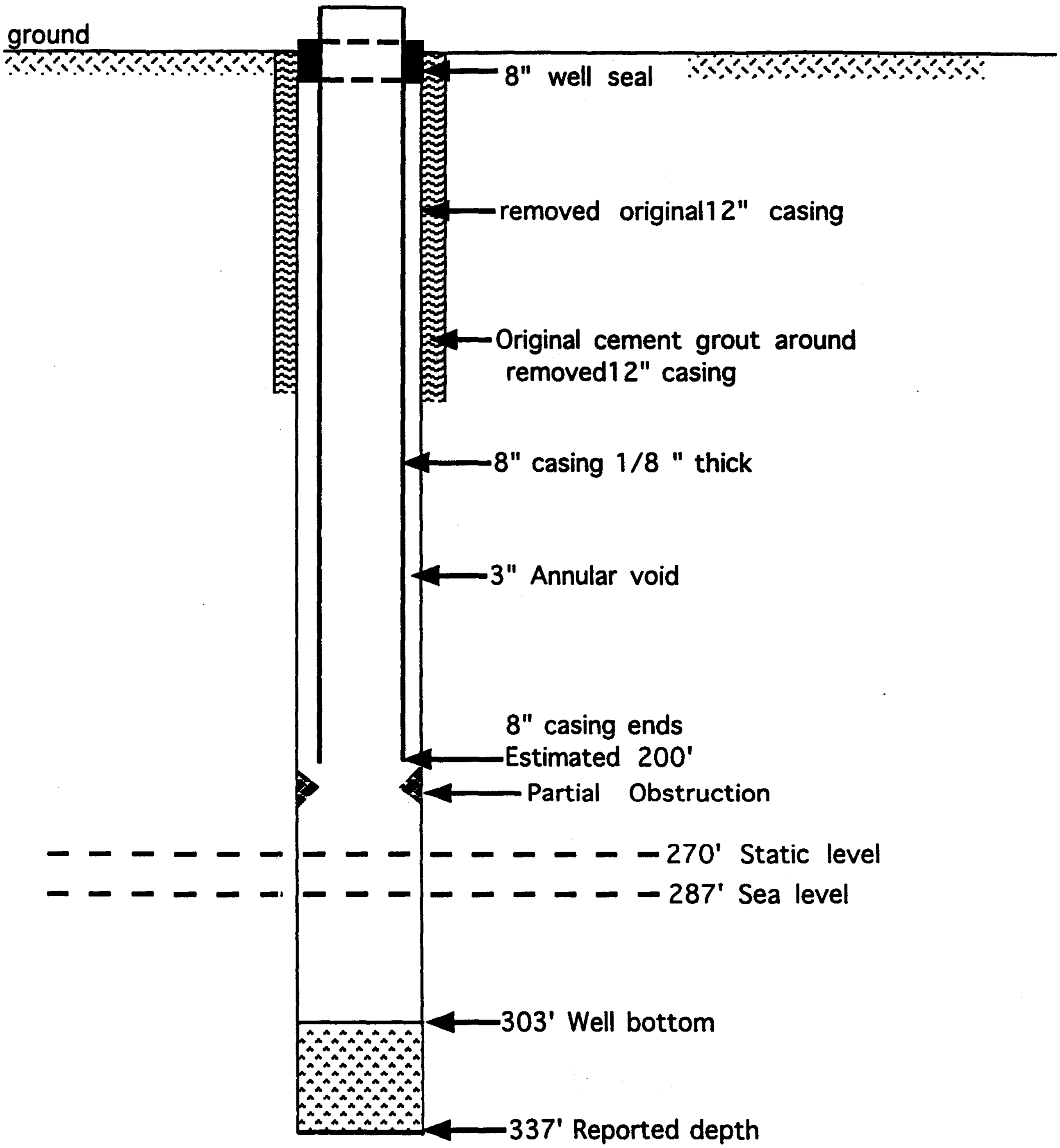
Casing Leak: If reinjection fluids entered the basal groundwater through a leak in the casing the anticipated changes in groundwater compositions would be expected to be very similar to those discussed above for reinjectate migration out of the injection zone. The primary difference between the two situations would be the possibility that there would be less mixing with oxygenated groundwater and less opportunity for the sulfide to be converted to sulfate. The degree of mixing would be highly dependent on the depth at which the leak occurred and, hence, no quantitative estimate of the amount of conversion can be made ahead of time. However, the appearance of elevated concentrations of dissolved sulfides in the monitoring wells would be clear evidence that a change had occurred to the basal groundwater system and that an evaluation of the likelihood of a leak should be evaluated.

In summary, the geochemical data do not indicate that there have been substantial changes in the shallow groundwater system that are indicated to be the result of production or reinjection of fluids associated with the current development activities in Lower Puna. The time series data do, however, provide a baseline against which future changes in groundwater quality can be compared, as well as test criteria that can be used, to determine whether fluid production or reinjection is having an effect on the basal water system around the geothermal reservoir.

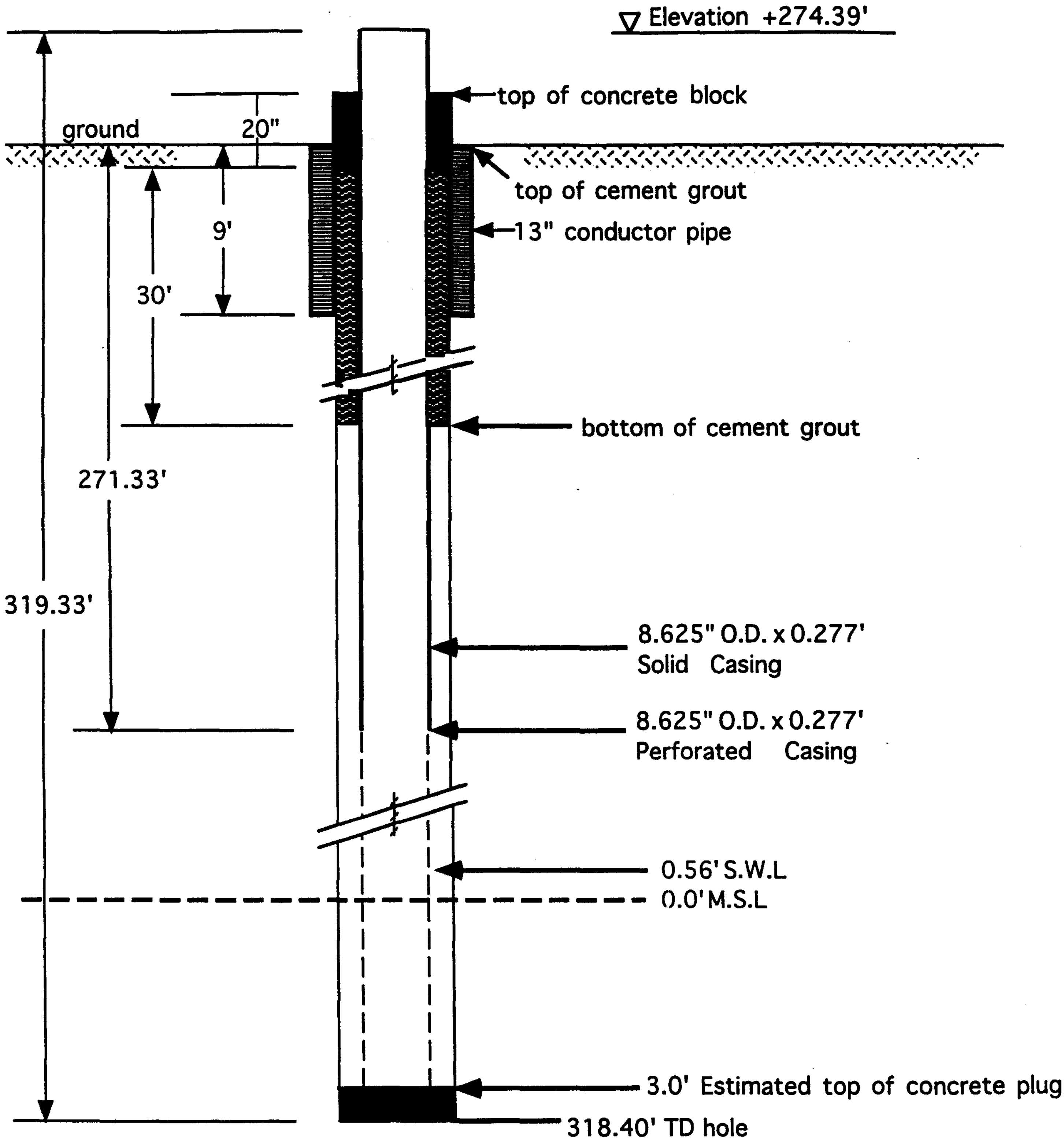
HAWAIIAN PARADISE WELL #1

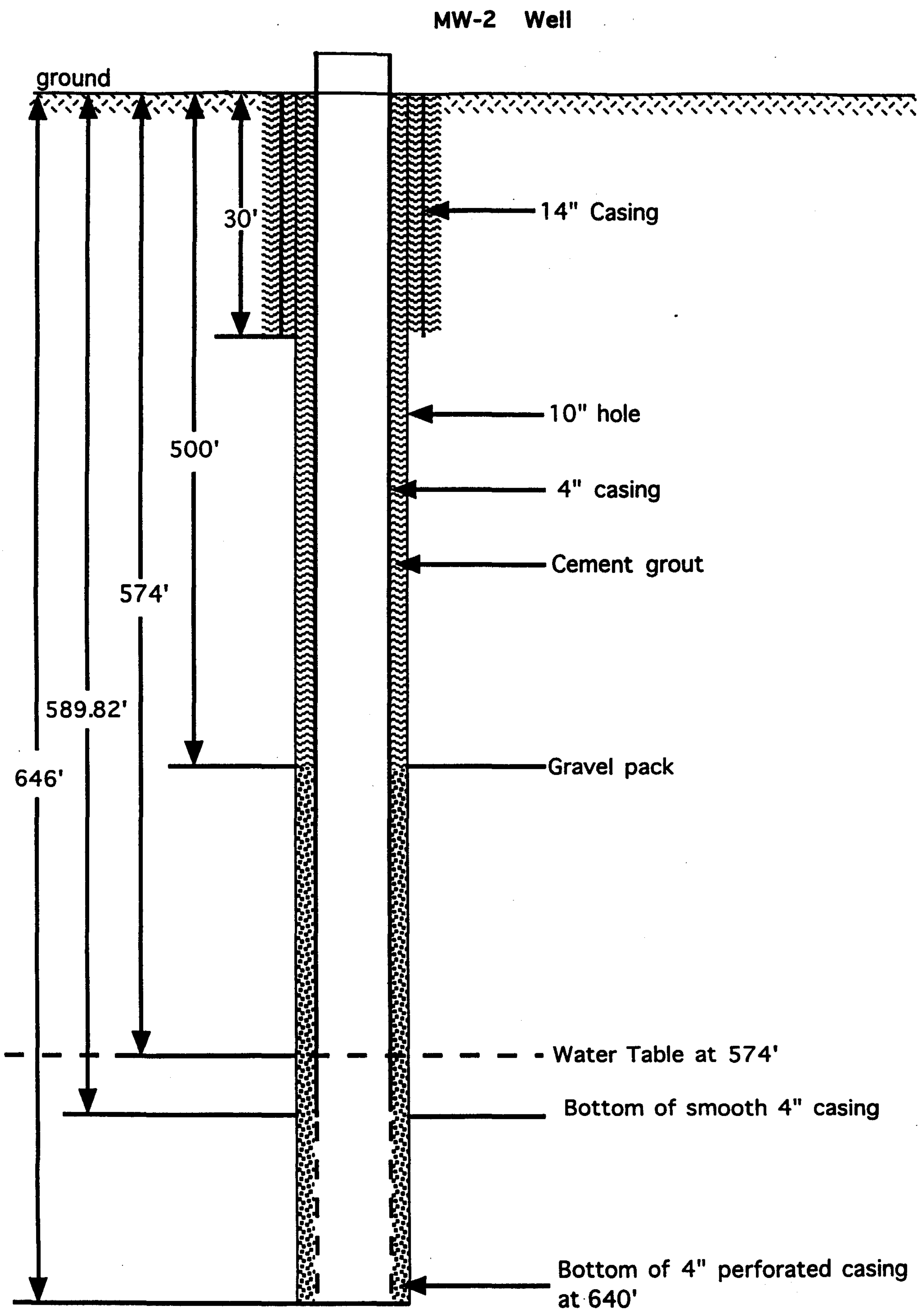


Kapoho Airstrip Well



MALAMA-KI EXPLORATORY WELL




MW-2 Well
ground
30'
500'
574'
589.82'
646'
14" Casing
10" hole
4" casing
Cement grout
Gravel pack
Water Table at 574'
Bottom of smooth 4" casing
Bottom of 4" perforated casing at 640'

POHOIKI WELL NO. 2881-01